Fibre Optic Communications - Introduction

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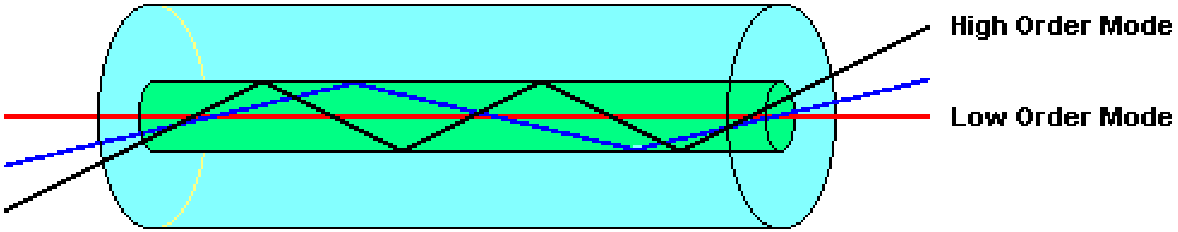
Module: Fibre Optic Communications

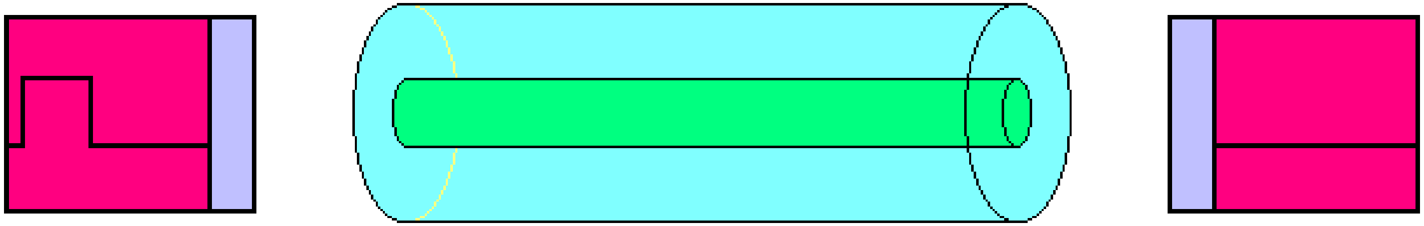
MSc/MEng – Digital Communication Systems

UNIVERSITY OF SUSSEX
SCHOOL OF ENGINEERING & INFORMATICS

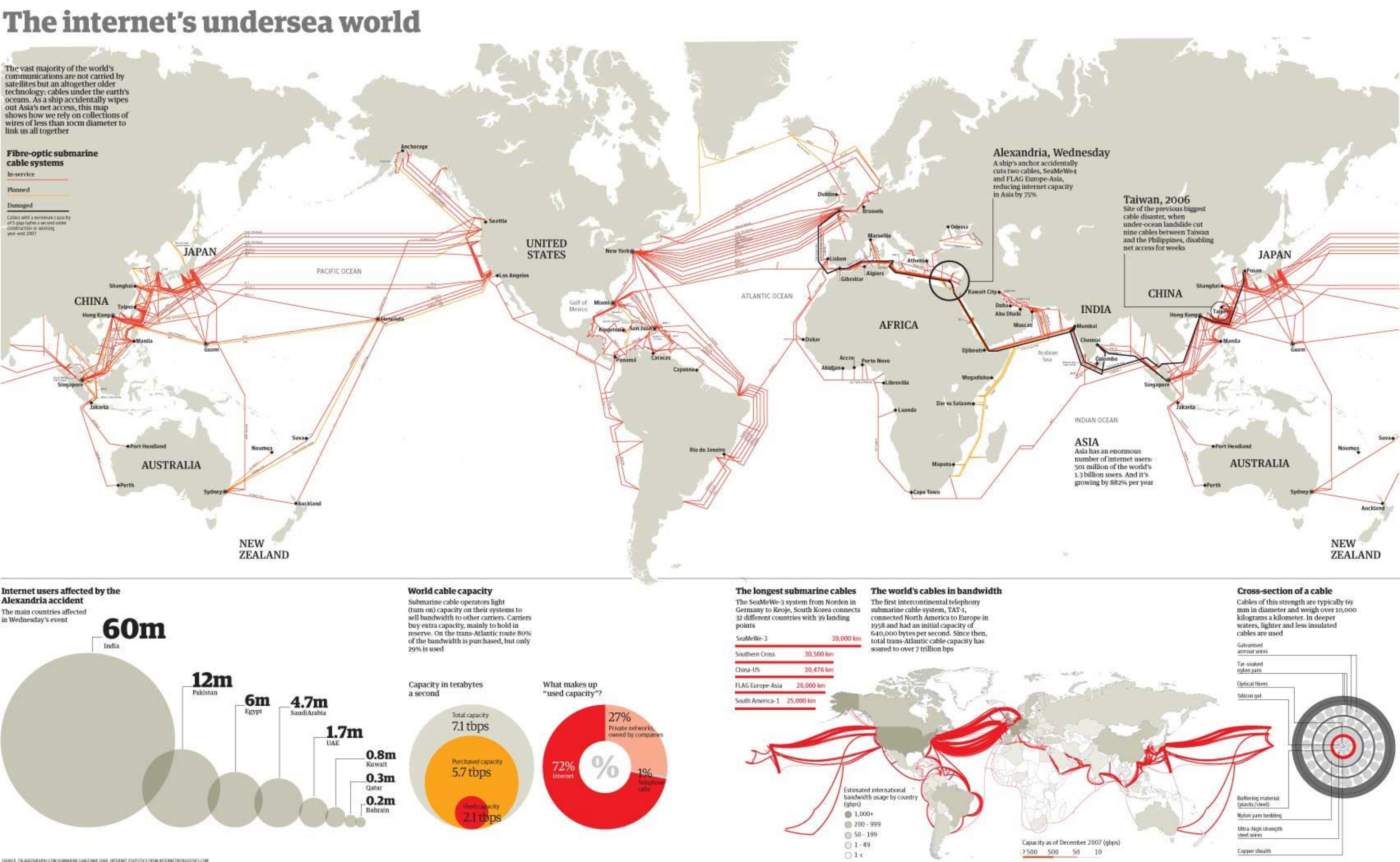
1st June 2017

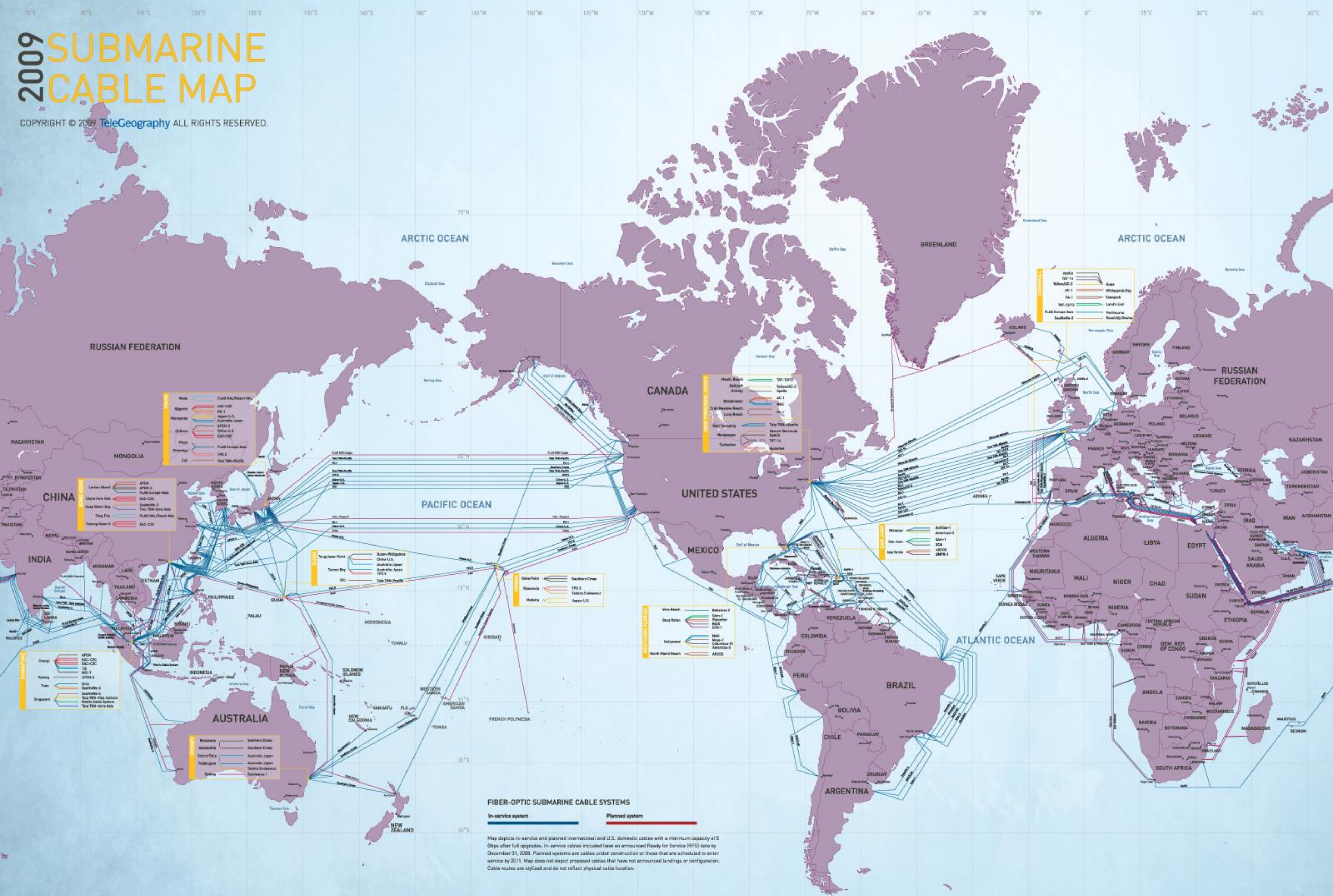
Problems to be avoided





DWDM Optical Fibre Communications
- Capacity: 7.1 terabytes per second Dec 2007



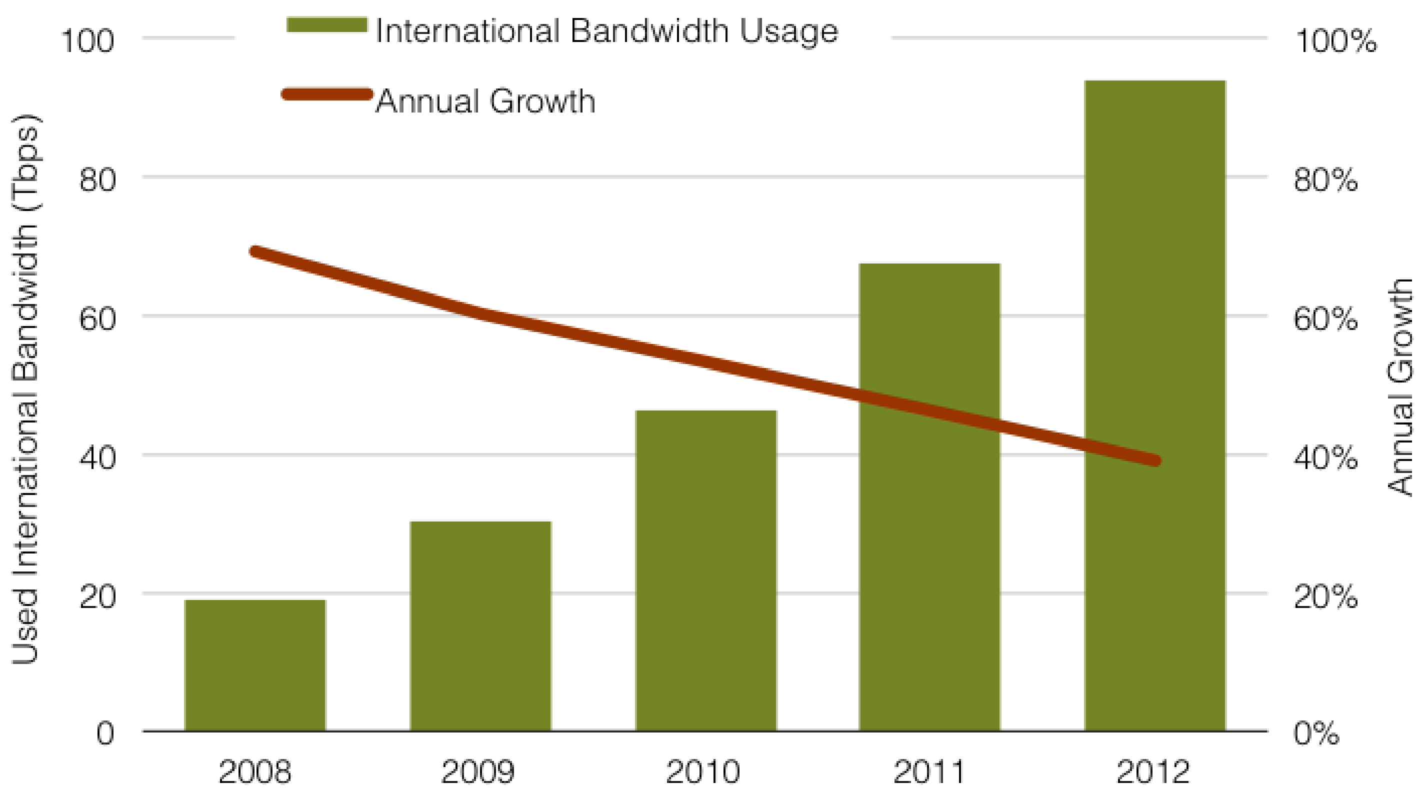


Global Data Integration Technology

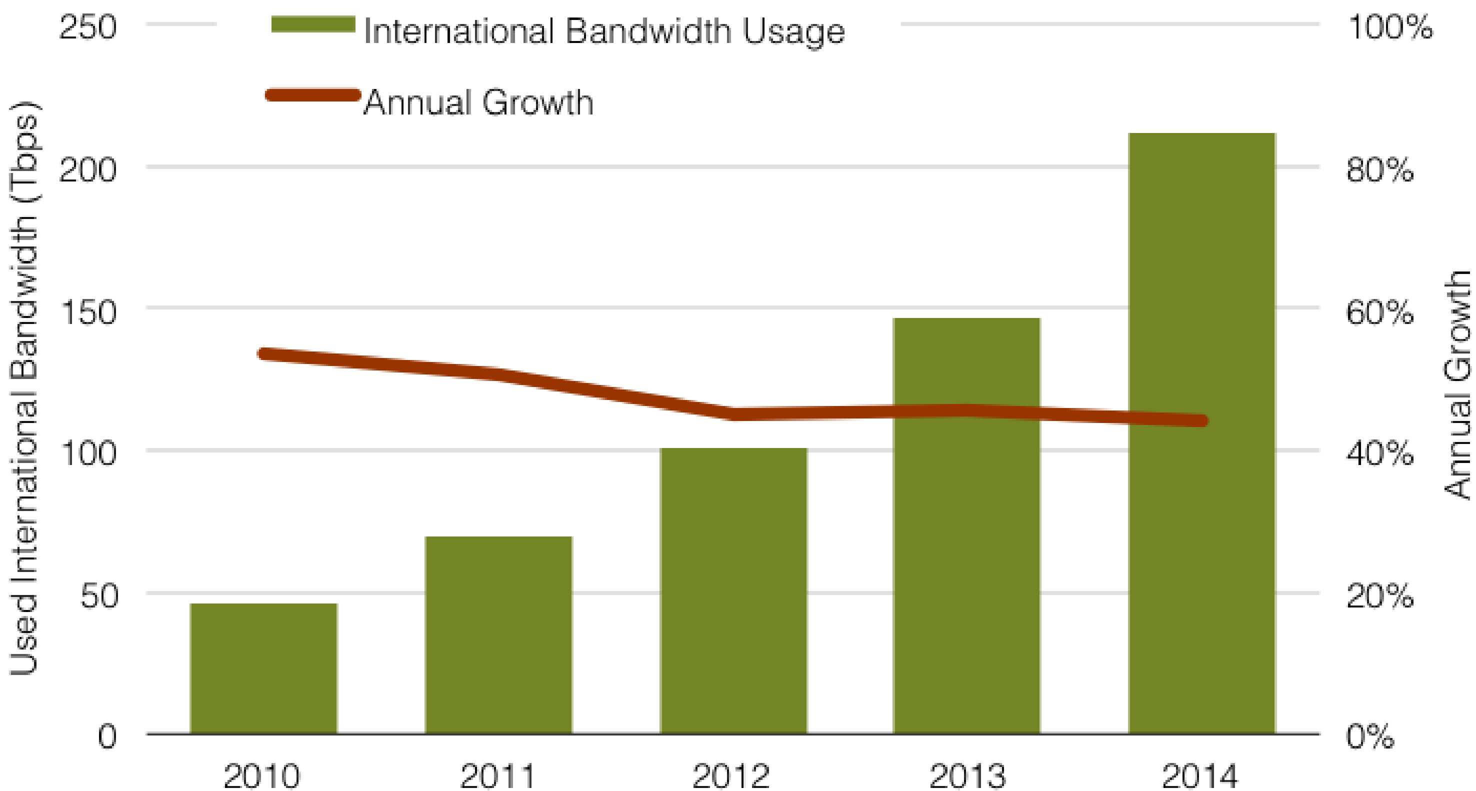
A NEW MAP of the SUBMARINE CABLES connecting the World, according to the best Authorities with all the latest Discoveries to the PRESENT PERIOD, 2015.

ISBN 978-1-886142-81-21 PRODUCTION TEAM Markus Krisetya, Larry Lairson, Alan Mauldin

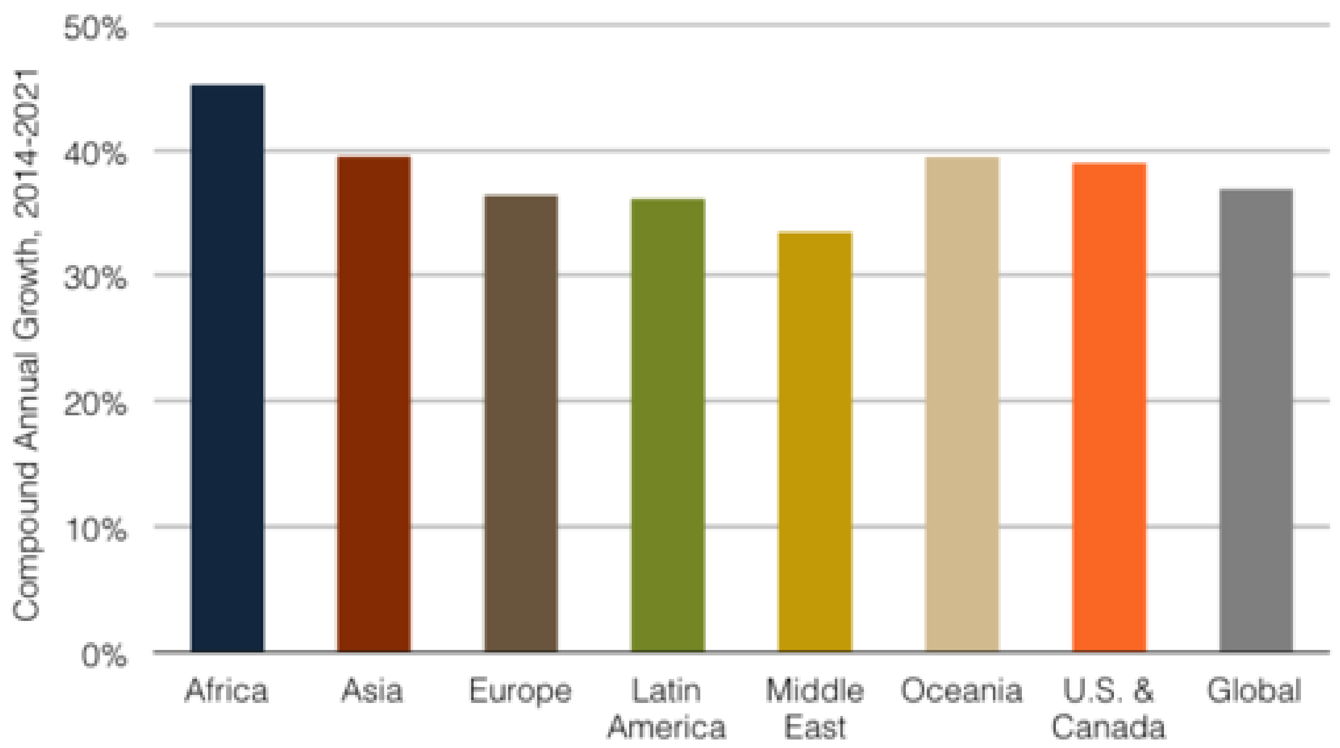
International Bandwidth 2012



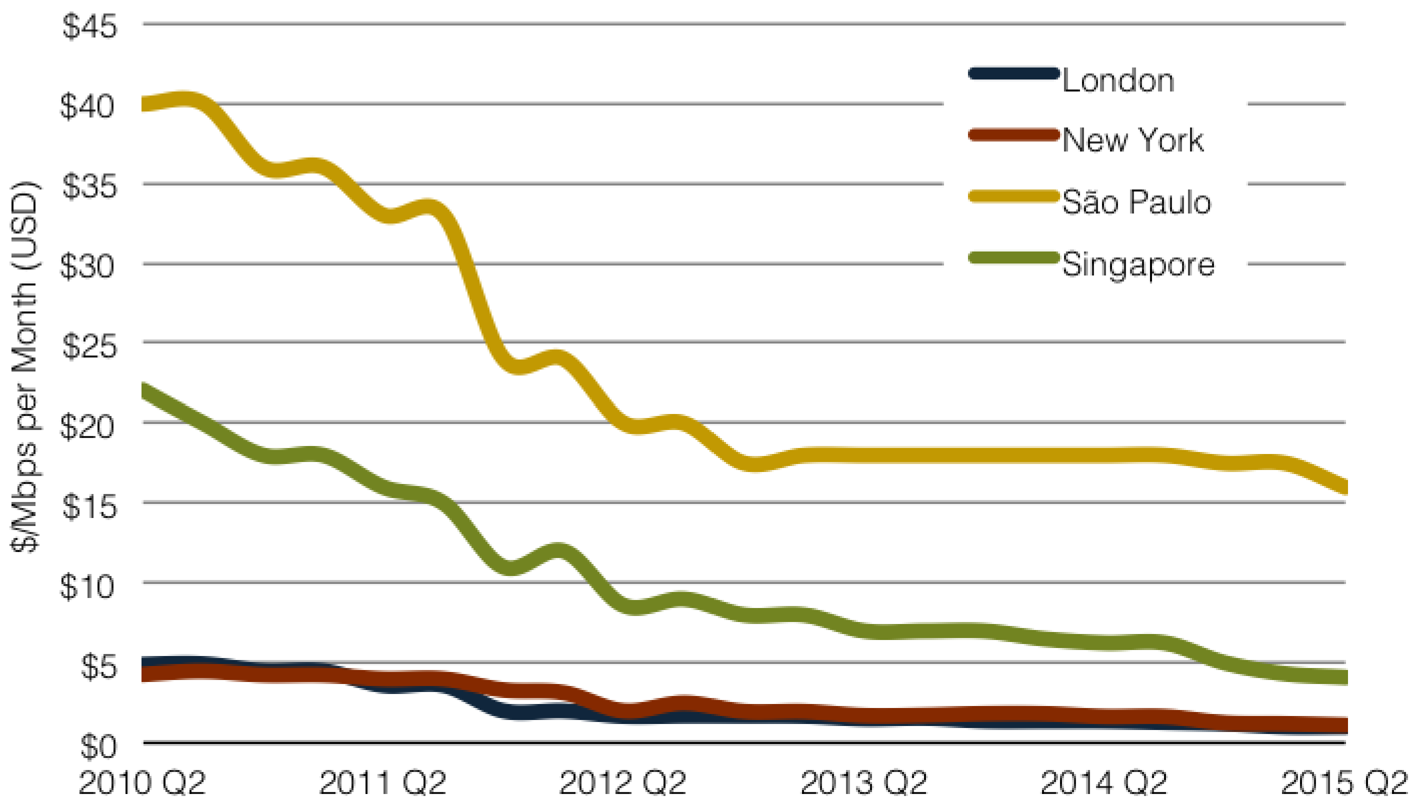
International Bandwidth 2014



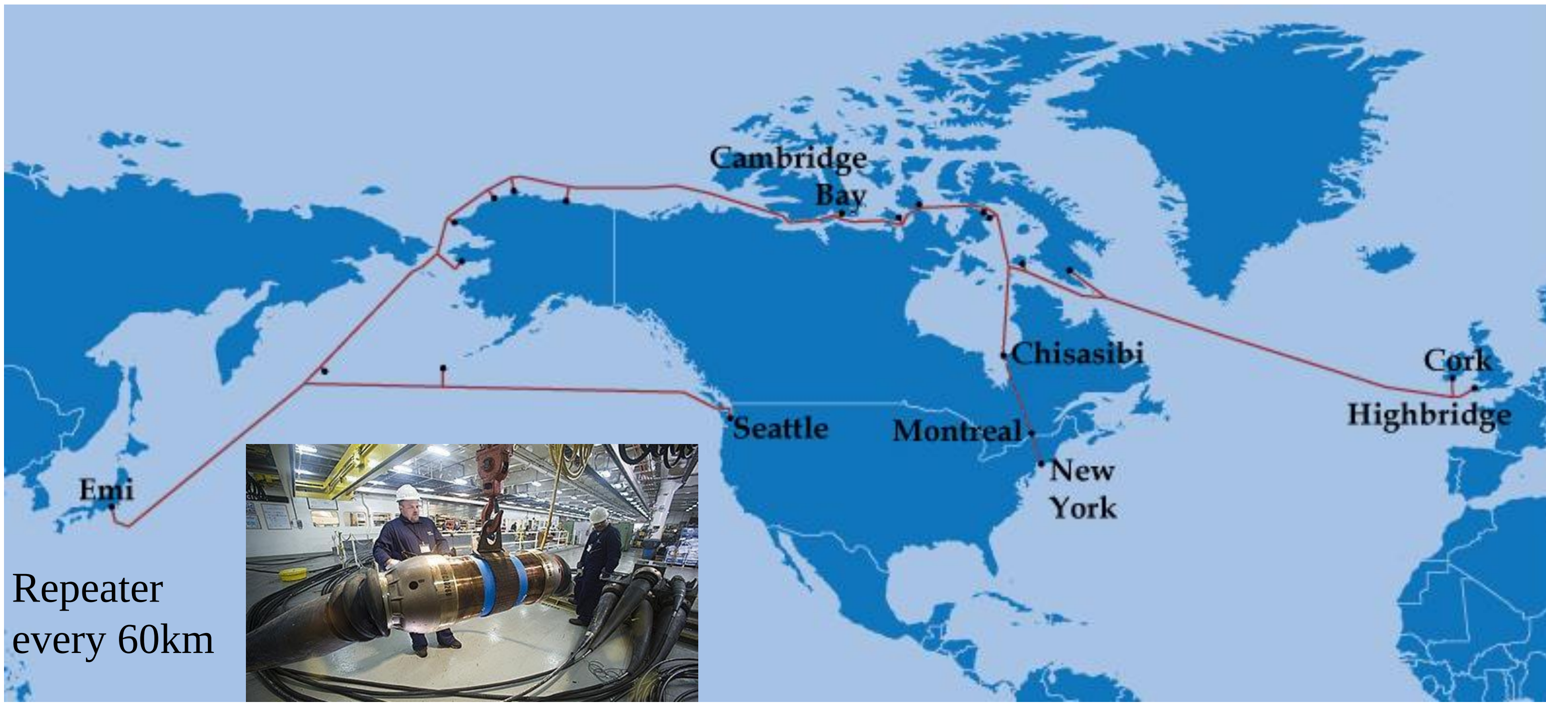
USED INTERNATIONAL BANDWIDTH GROWTH BY REGION, 2014-2021



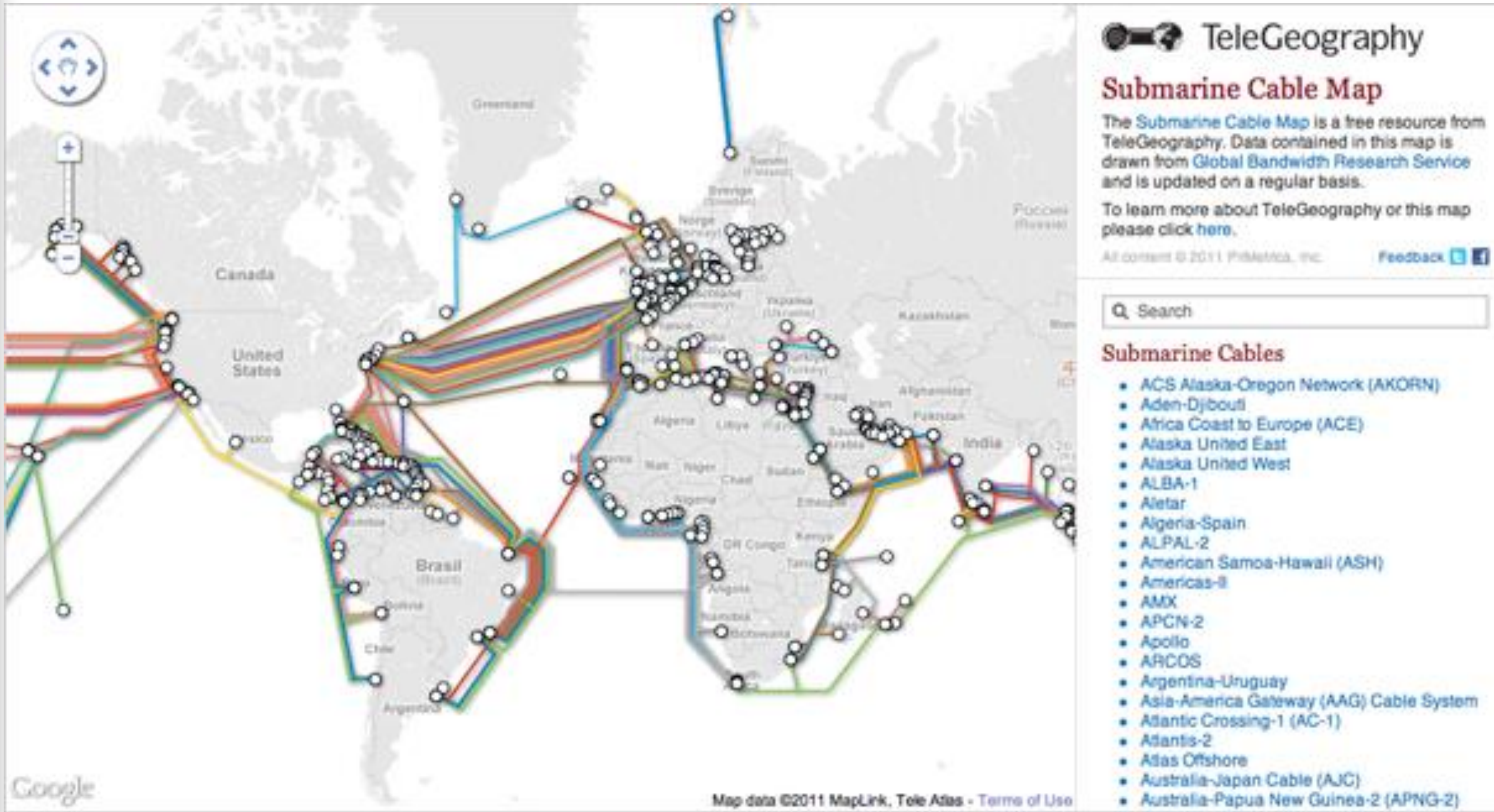
MEDIAN 10 GIGE IP TRANSIT PRICES IN MAJOR CITIES, Q2 2012-Q2 2015



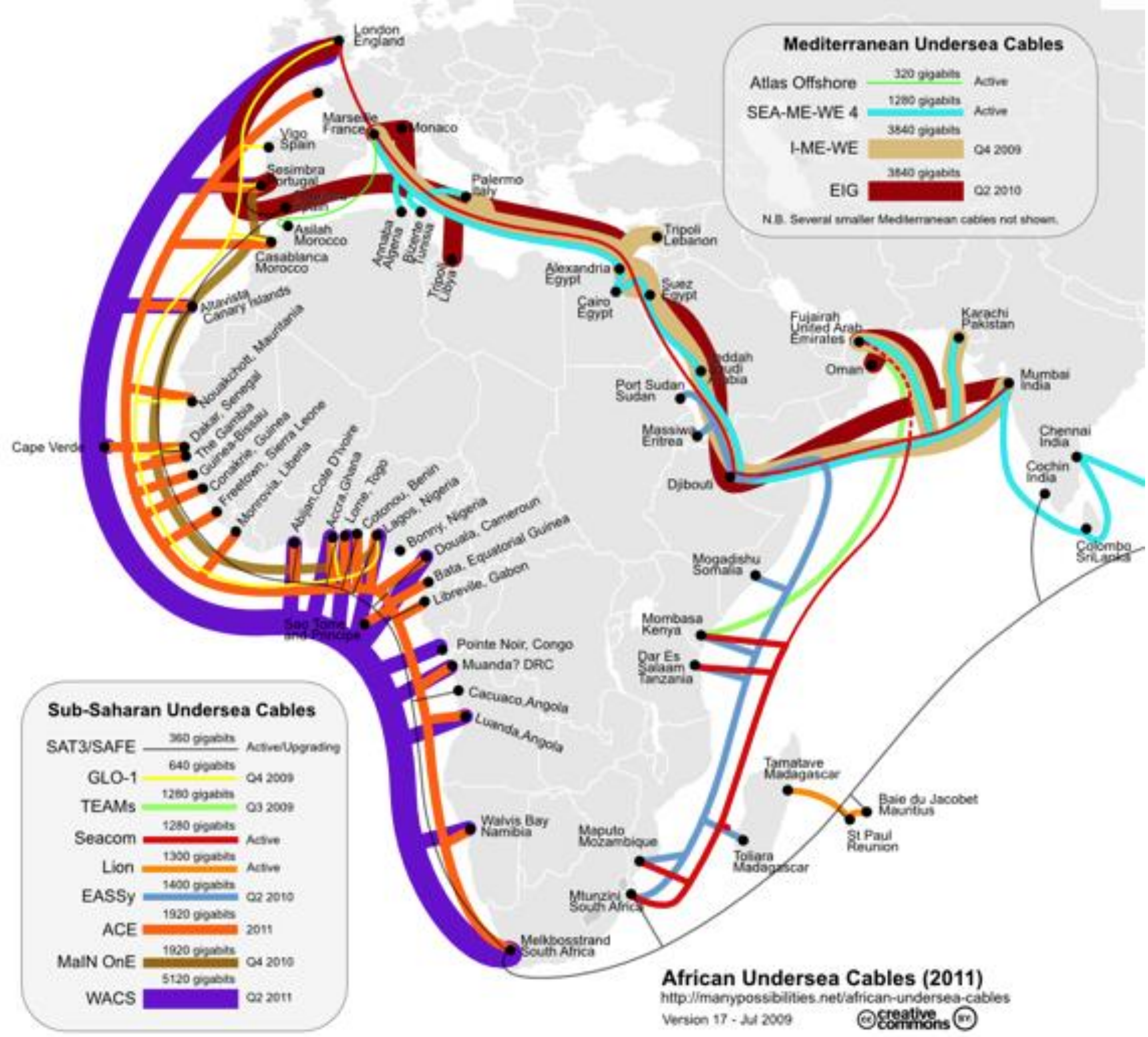
Arctic Fibre is deploying state of the art technology utilizing 100 gigabit wavelengths to construct a system with a capacity of 24 terabits/s.



The construction of the system is beginning in May 2014 and is scheduled to be in service in January 2016.

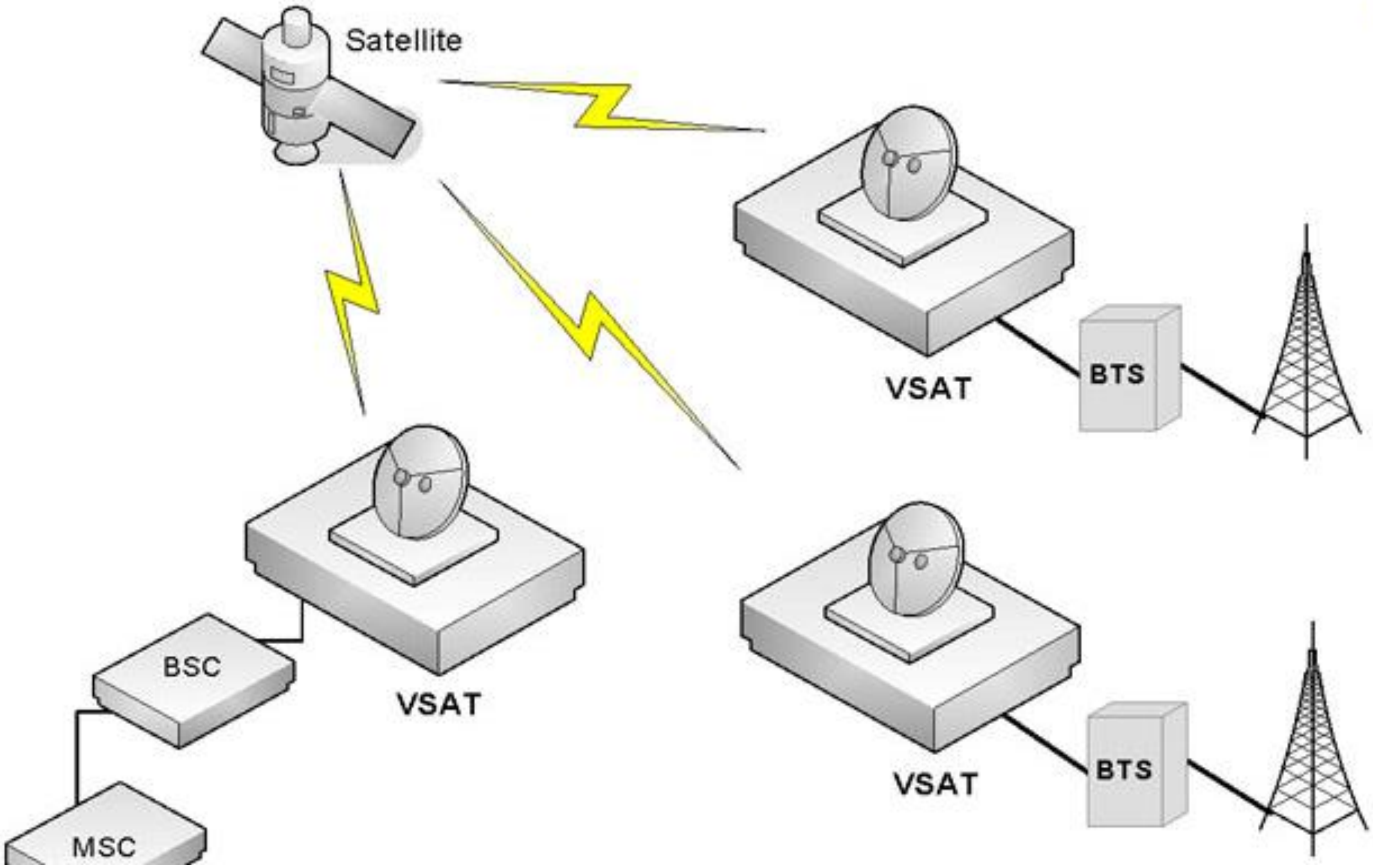


http://www.submarinecablemap.com/



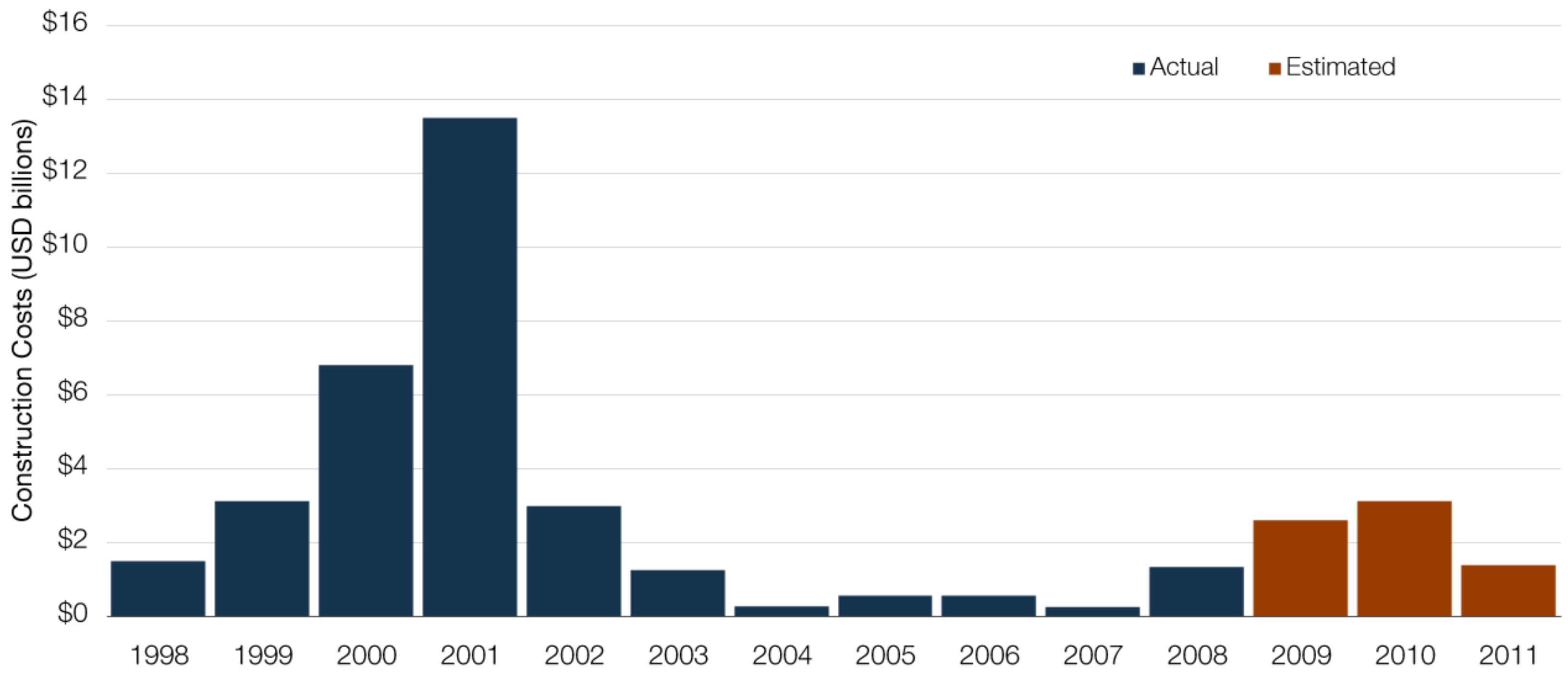
Mediterranean Undersea Cables
Atlas Offshore 320 gigabits Active
SEA-ME-WE 4 1280 gigabits Active
I-ME-WE 3840 gigabits Q4 2009
EIG 3840 gigabits Q2 2010
N.B. Several smaller Mediterranean cables not shown.
Sub-Saharan Undersea Cables
SAT3/SAFE 360 gigabits Active/Upgrading
GLO-1 640 gigabits Q4 2009
TEAMs 1280 gigabits Q3 2009
Seacom 1280 gigabits Active
Lion 1300 gigabits Active
EASSy 1400 gigabits Q2 2010
ACE 1920 gigabits 2011
MaIN OnE 1920 gigabits Q4 2010
WACS 5120 gigabits Q2 2011
London England
Marseille France
Monaco
Vigo Spain
Sesimbra Portugal
Asilah Morocco
Casablanca Morocco
Palermo Italy
Tripoli Lebanon
Alexandria Egypt
Cairo Egypt
Suez Egypt
Port Sudan Sudan
Massiwa Eritrea
Djibouti
Fujairah United Arab Emirates
Oman
Karachi Pakistan
Mumbai India
Chennai India
Cochin India
Colombo Sri Lanka
Mogadishu Somalia
Mombasa Kenya
Dar Es Salaam Tanzania
Tamatave Madagascar
Baie du Jacobet Mauritius
St Paul Reunion
Toliara Madagascar
Maputo Mozambique
Mtunzini South Africa
Melkbosstrand South Africa
Walvis Bay Namibia
Luanda, Angola
Cacuaco, Angola
Muanda? DRC
Pointe Noir, Congo
Sao Tome and Principe
Libreville, Gabon
Bata, Equatorial Guinea
Douala, Cameroun
Bonny, Nigeria
Lagos, Nigeria
Cotonou, Benin
Lome, Togo
Accra, Ghana
Abijan, Cote D'Ivoire
Monrovia, Liberia
Freetown, Sierra Leone
Conakrie, Guinea
Guinea-Bissau
The Gambia
Dakar, Senegal
Nouakchott, Mauritania
Cape Verde
Altavista Canary Islands
African Undersea Cables (2011)
http://manypossibilities.net/african-undersea-cables
Version 17 - Jul 2009
creative commons

VSAT

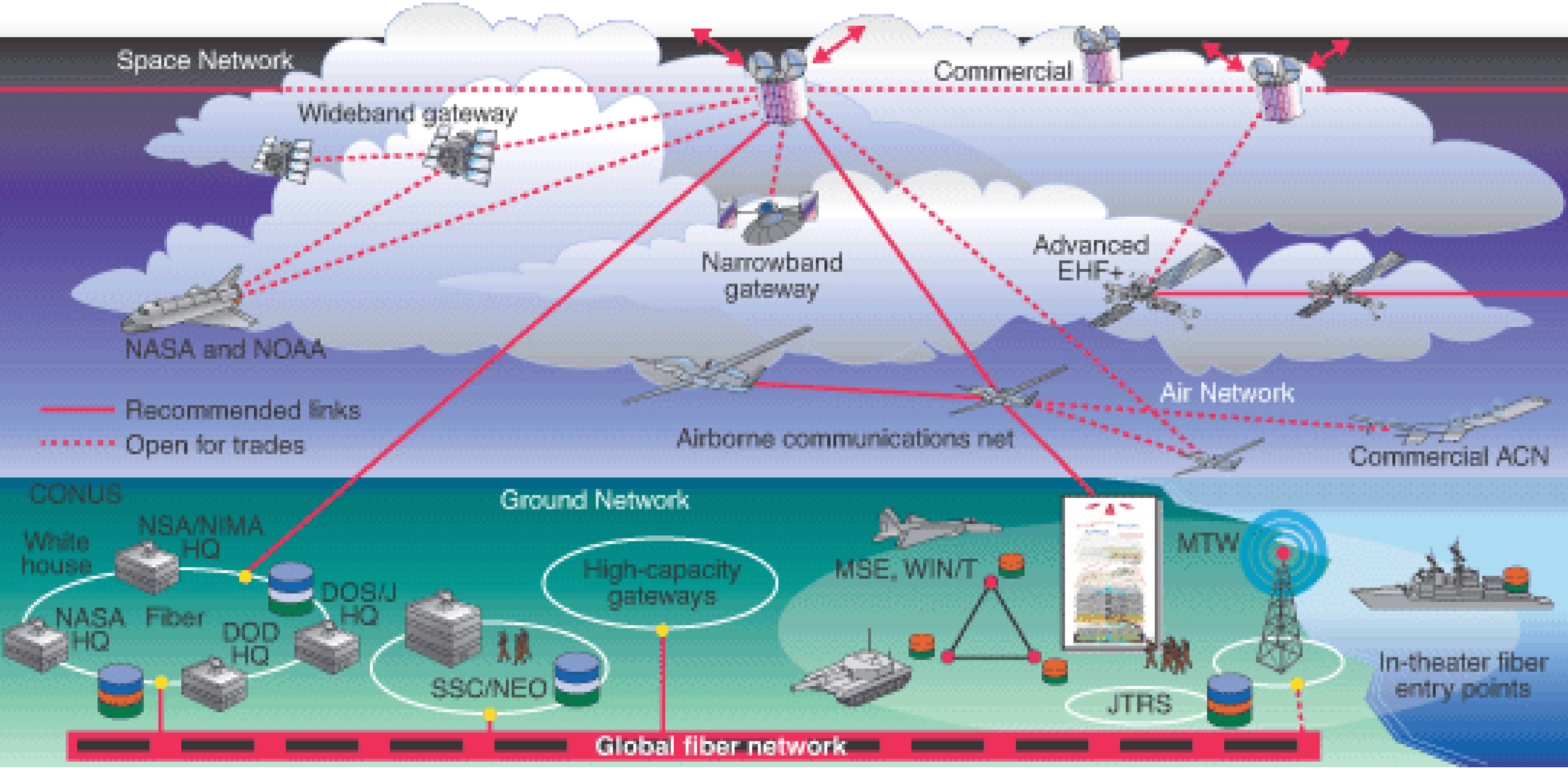


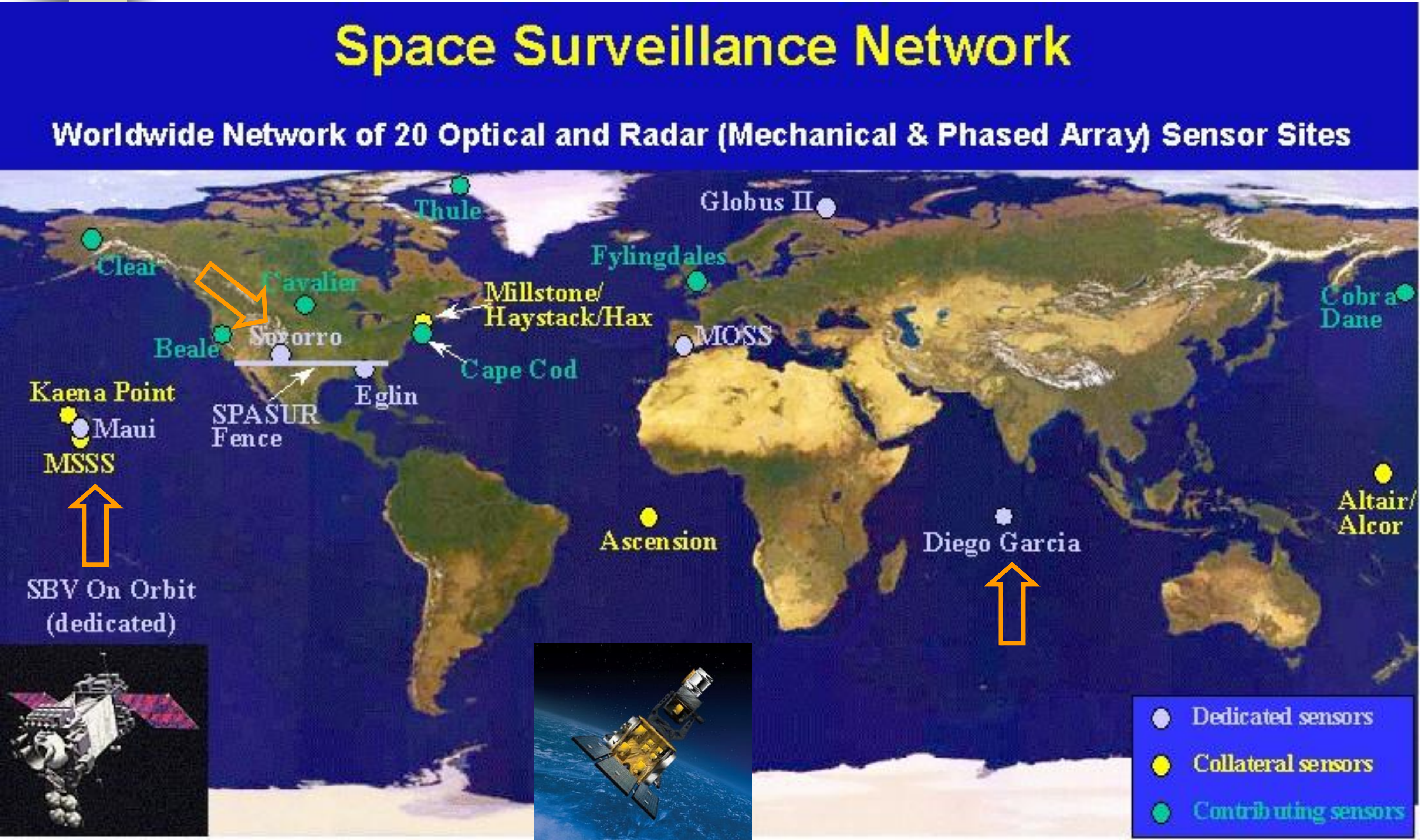

Call Forwarding
Instant Messenge
PC - to - PC
Fax - to - PC
IP voice conferencing
SMS in/out and notification
WWW
Internet Roaming
OC Global Network
CPE
OC User
Phone - to - PC
Phone - to - Phone
OC No./PIN
PC - to - Phone
DID

Construction cost of submarine cables, 1998-2011



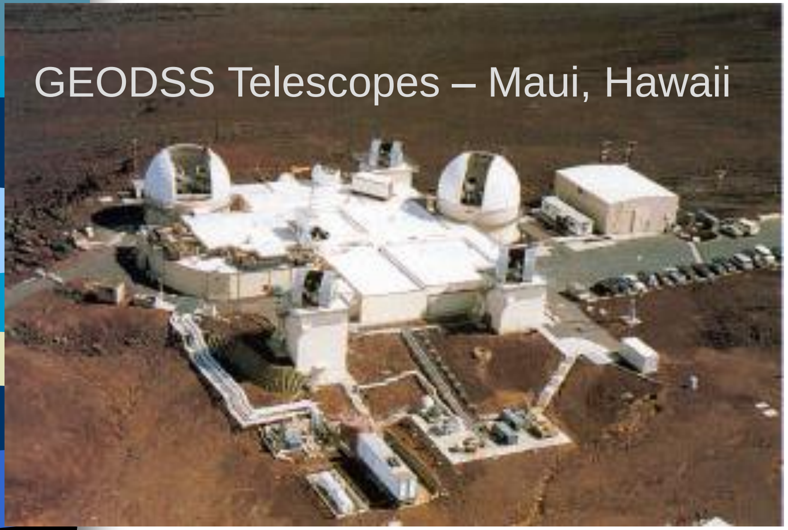
The Global Fibre Backbone integrates global communications




Space Surveillance Network
Worldwide Network of 20 Optical and Radar (Mechanical & Phased Array) Sensor Sites
Thule
Globus II
Clear
Cavalier
Fylingdales
Millstone/
Haystack/Hax
Cobra
Dane
Socorro
Beale
MOSS
Cape Cod
Eglin
Kaena Point
Maui
MSSS
SPASUR
Fence
Ascension
Diego Garcia
Altair/
Alcor
SBV On Orbit
(dedicated)
Dedicated sensors
Collateral sensors
Contributing sensors

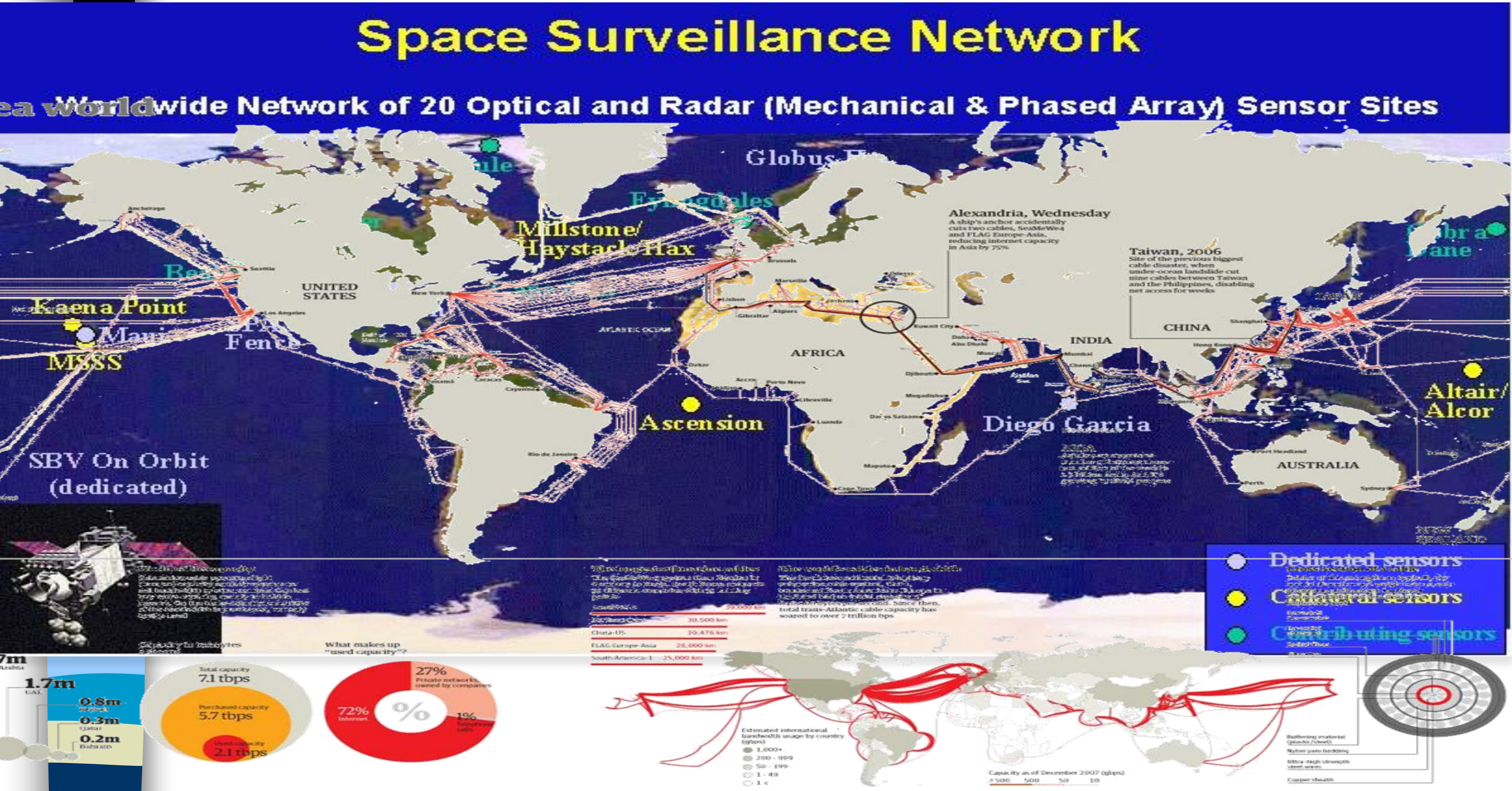
Ground-*Based* Electro-Optical Deep *Space* Surveillance (GEODSS) - Diego Garcia / Maui / Socorro (check orange arrows on previous slide)

- Primary Mission: Space Surveillance
- Supports Air Force Space Command (AFSPC) as a dedicated Deep Space (DS) sensor
- GEODSS brings together the telescope, low-light-level cameras, and computers



Inside Diego Garcia GEODSS

Global Data Integration Technology



Space Surveillance

•Conduct space surveillance from space

•Surveillance of entire geosynchronous belt

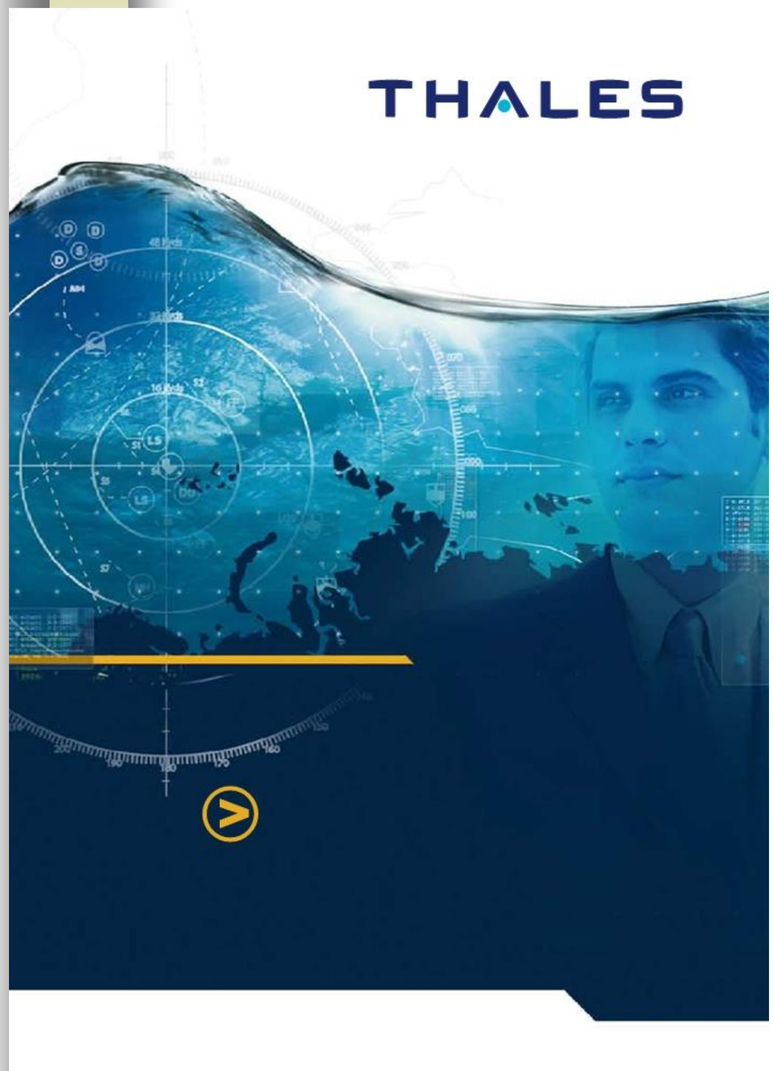
•Assured access to objects of military interest

NAVSPACE Fence

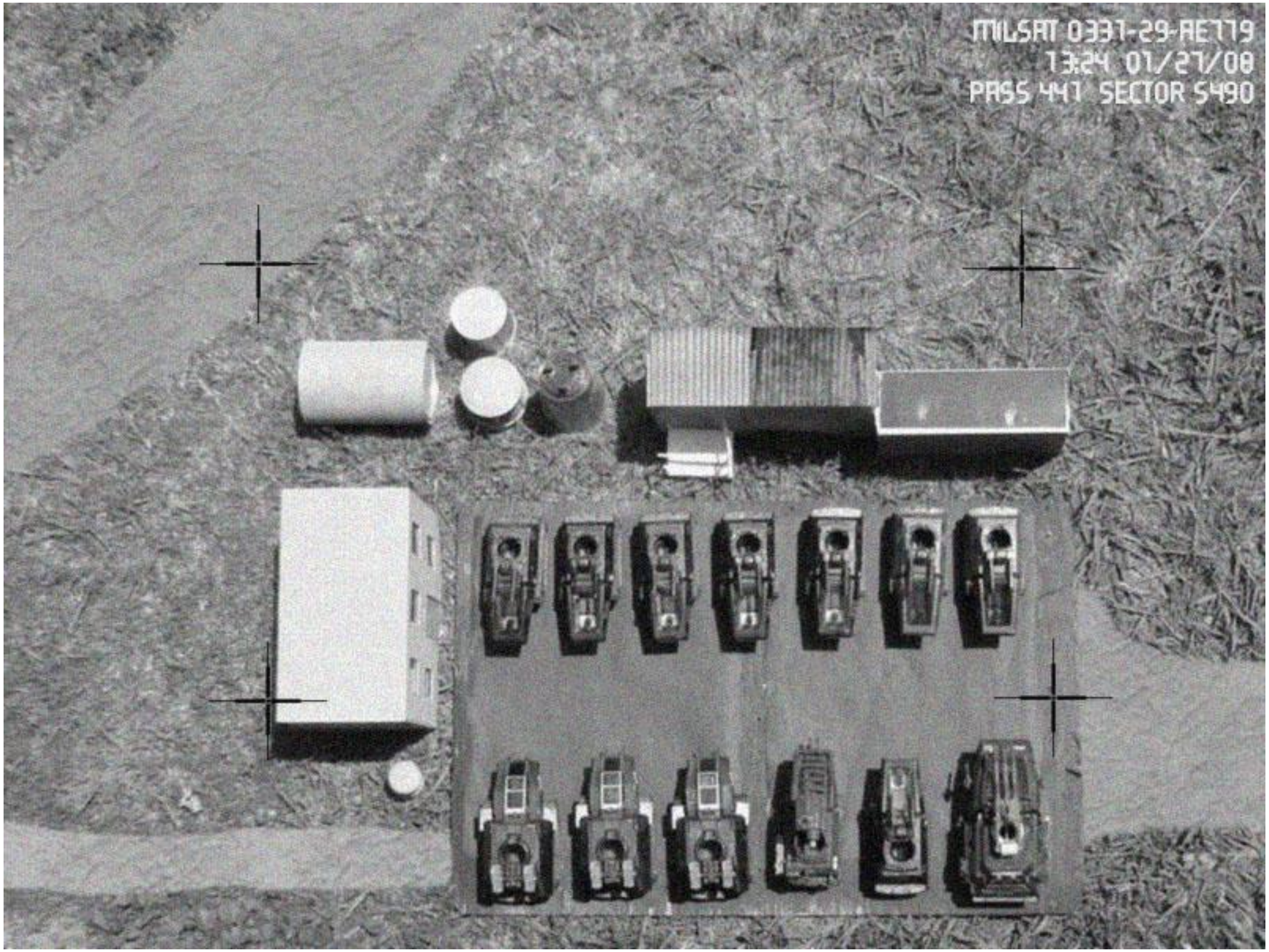
• Provides up to date satellite orbital elements to Fleet and Fleet Marine forces

• Supports US Space Command as part of nation's worldwide Space Surveillance Network

Ubiquitous Sonar Surveillance Systems



Satellite Image of Military Vehicles



As Important as the Wheel

Dr Charles Kao di STL, ora Nortel

A graduate of Woolwich Polytechnic won the Nobel Prize for Physics. Charles Kuen Kao's work with fibre optics paved the way for lightning-fast broadband.
Professor Kao was honoured for his breakthroughs involving the transmission of light in fibre optics.

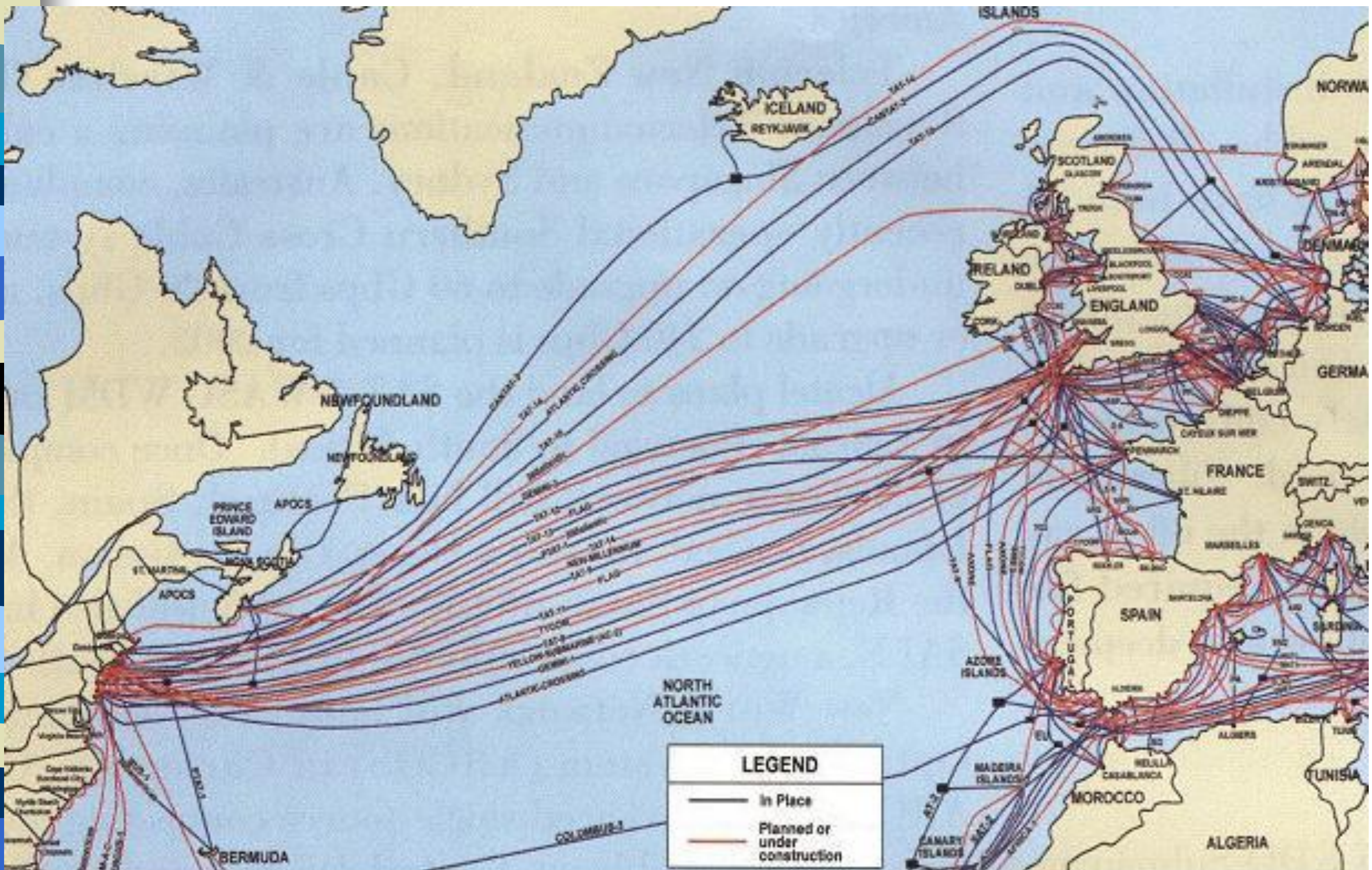
He was the first person to develop efficient fibre-optic cables and as a result of his work more than a billion kilometres of optical cables carry super-fast broadband internet data to and from households and offices around the world.

GCHQ

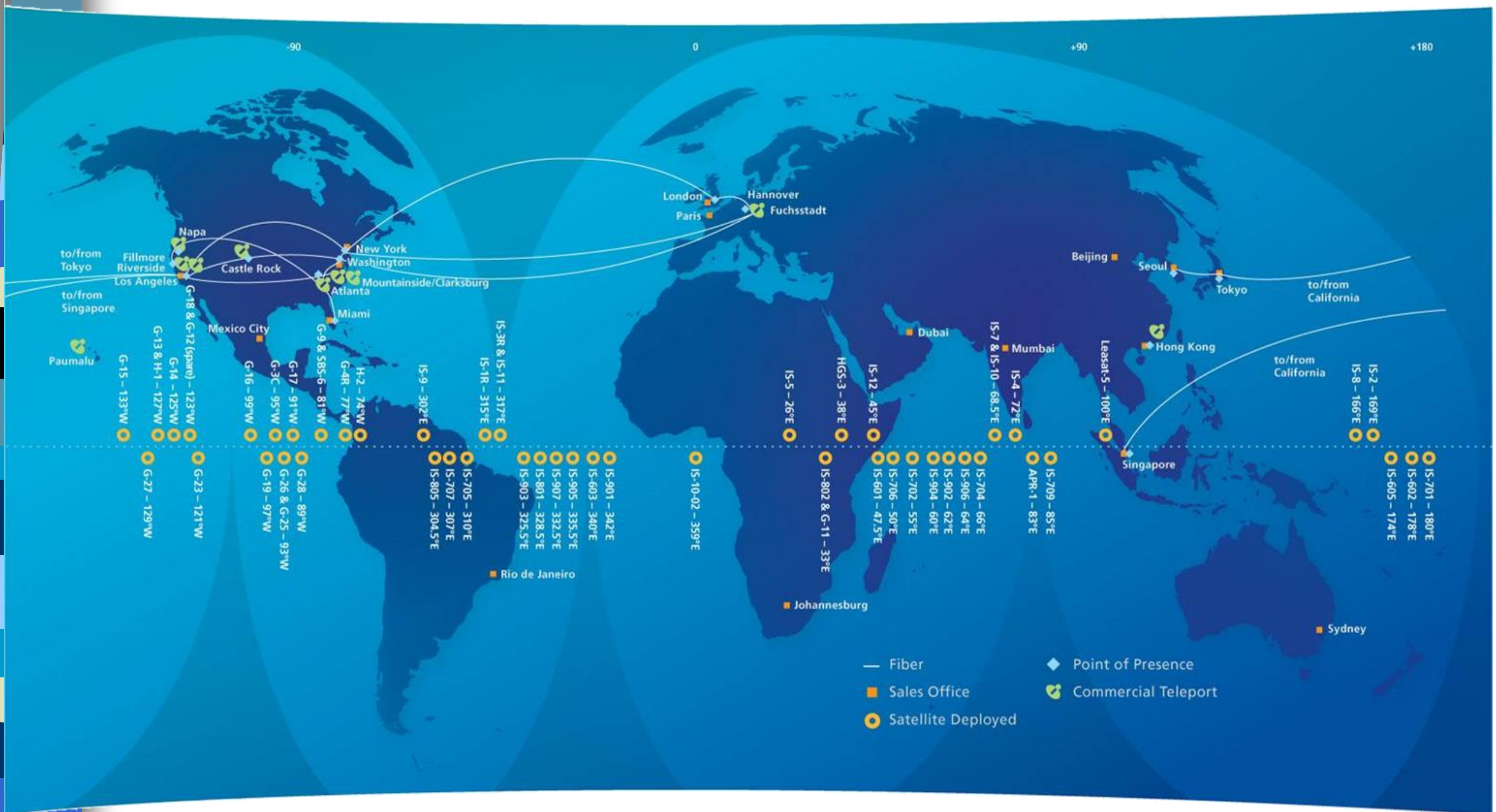
GCHQ's headquarters are in Cheltenham, Gloucestershire. There are two much smaller sites in Cornwall and Yorkshire but most of the 5500 staff work at the impressive state of the art building at Benhall in Cheltenham.

http://www.submarinecablemap.com/

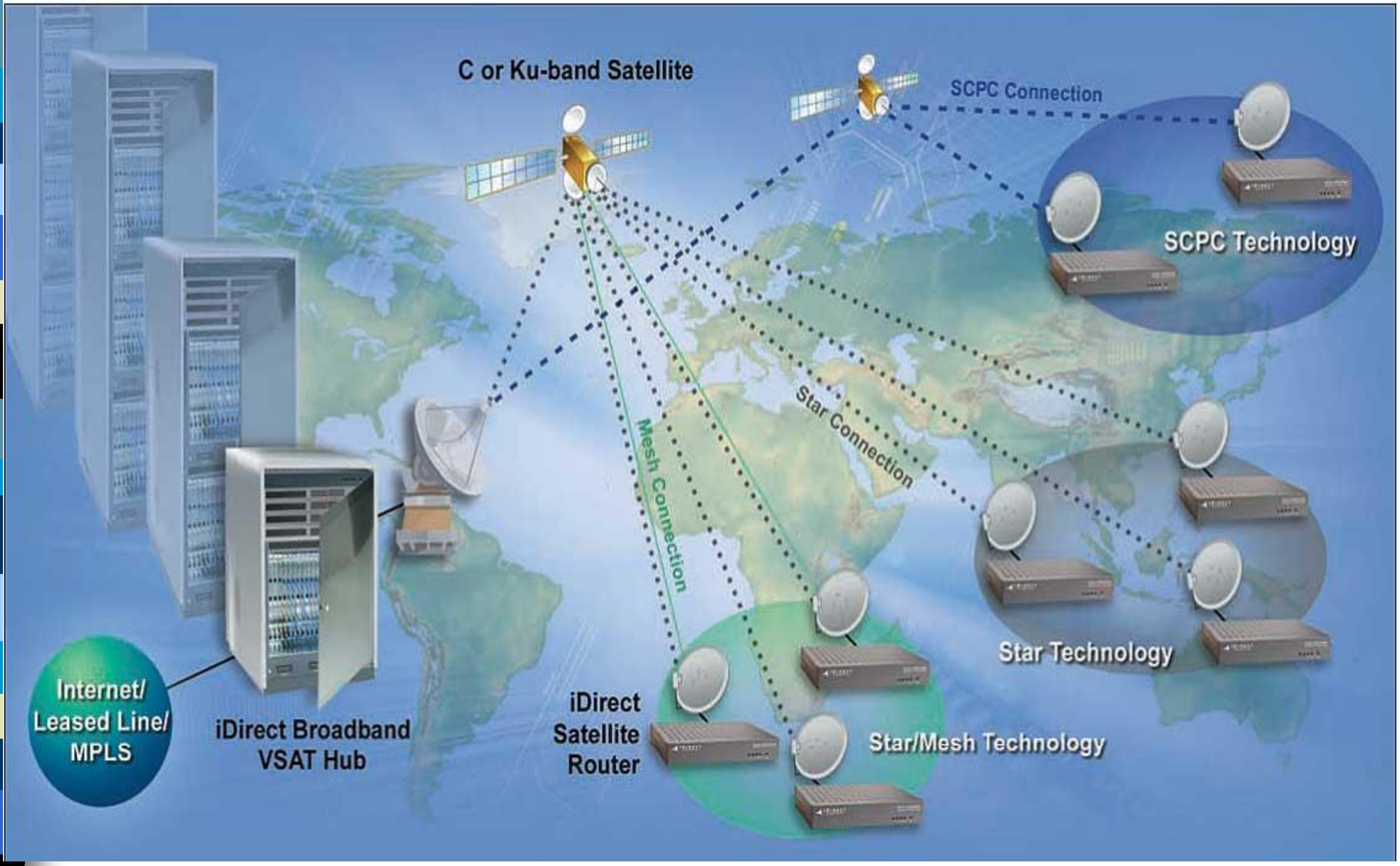
Trans-Atlantic Fibre Optic Cables



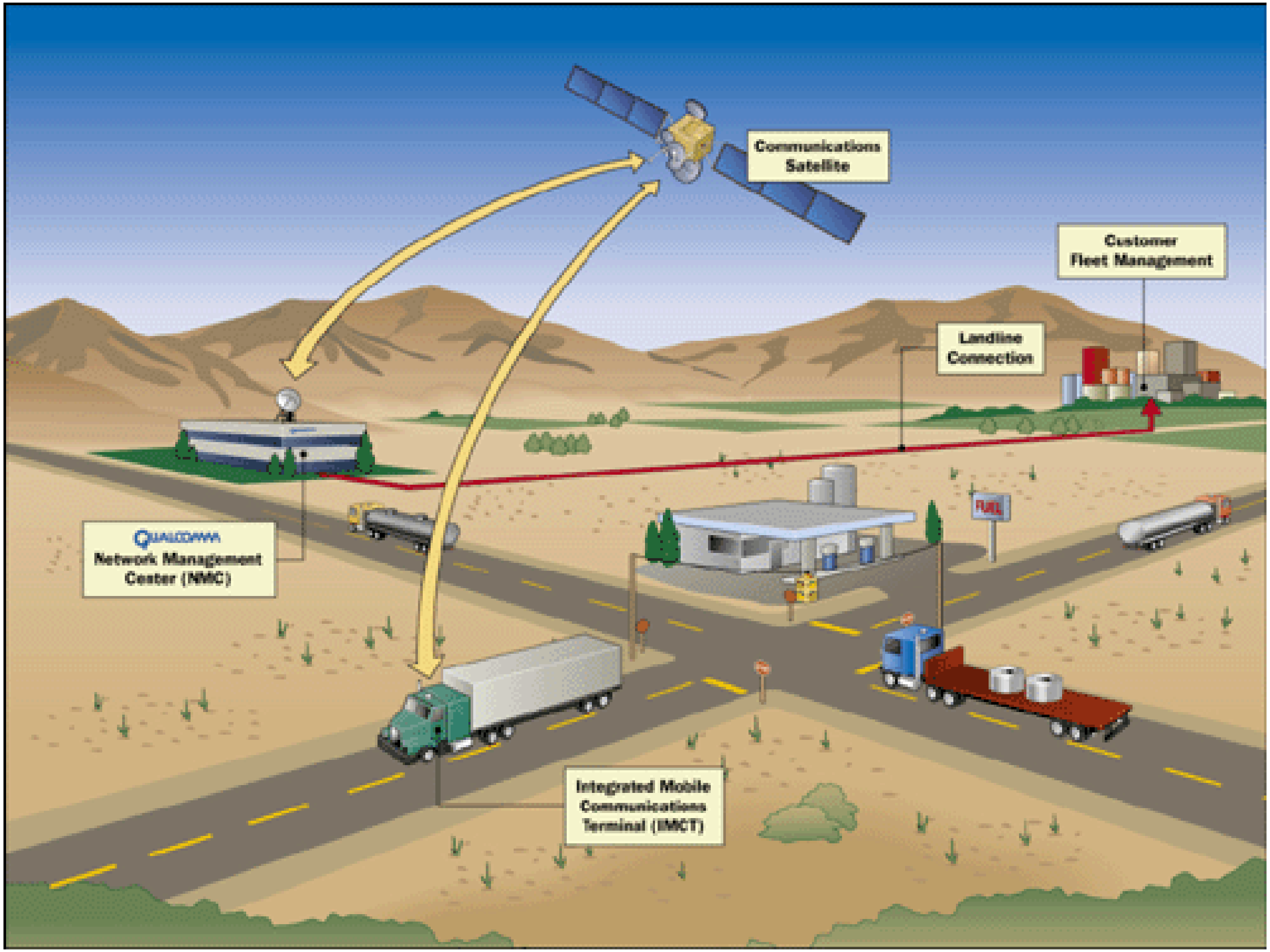
The Intelsat Satellite Network 2008

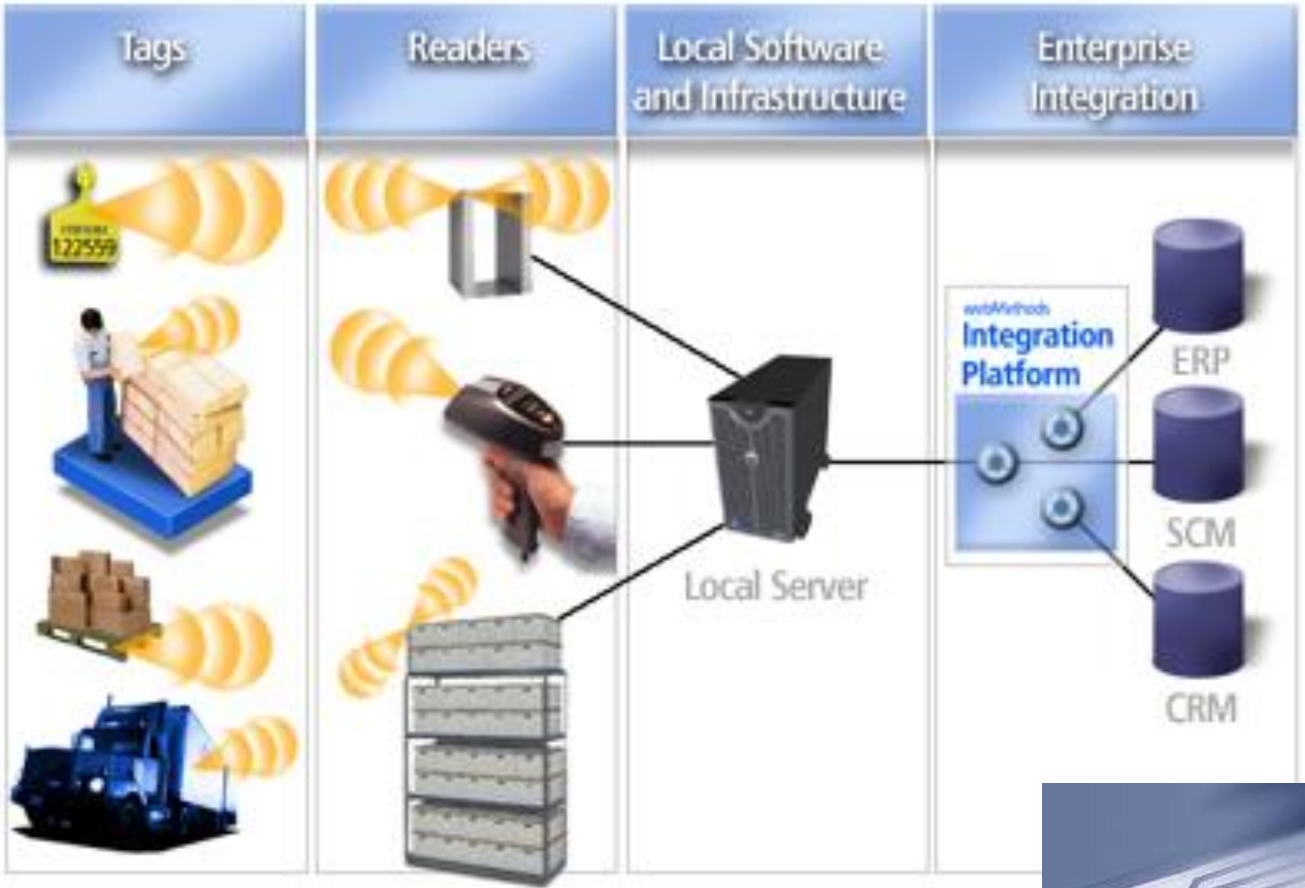


Very Small Aperture Terminal (VSAT)

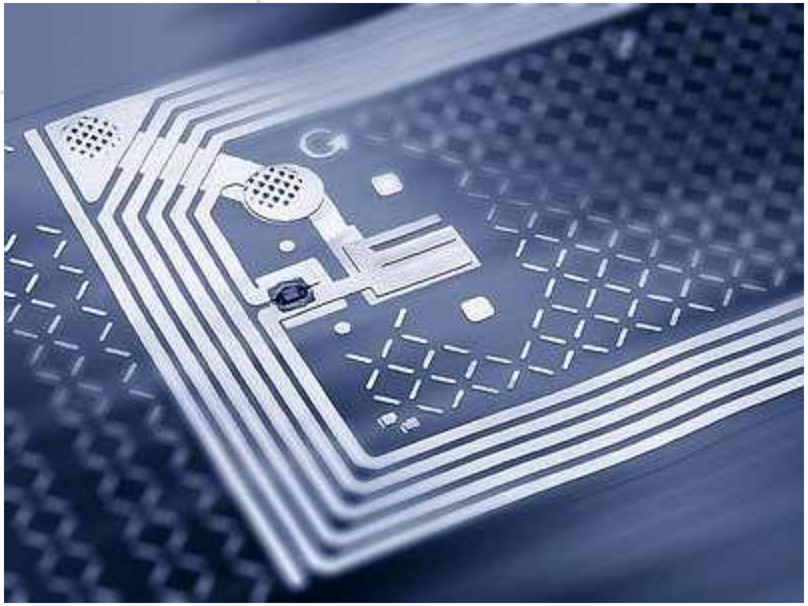


Untethered Trailer Tracking Wireless Terrestrial

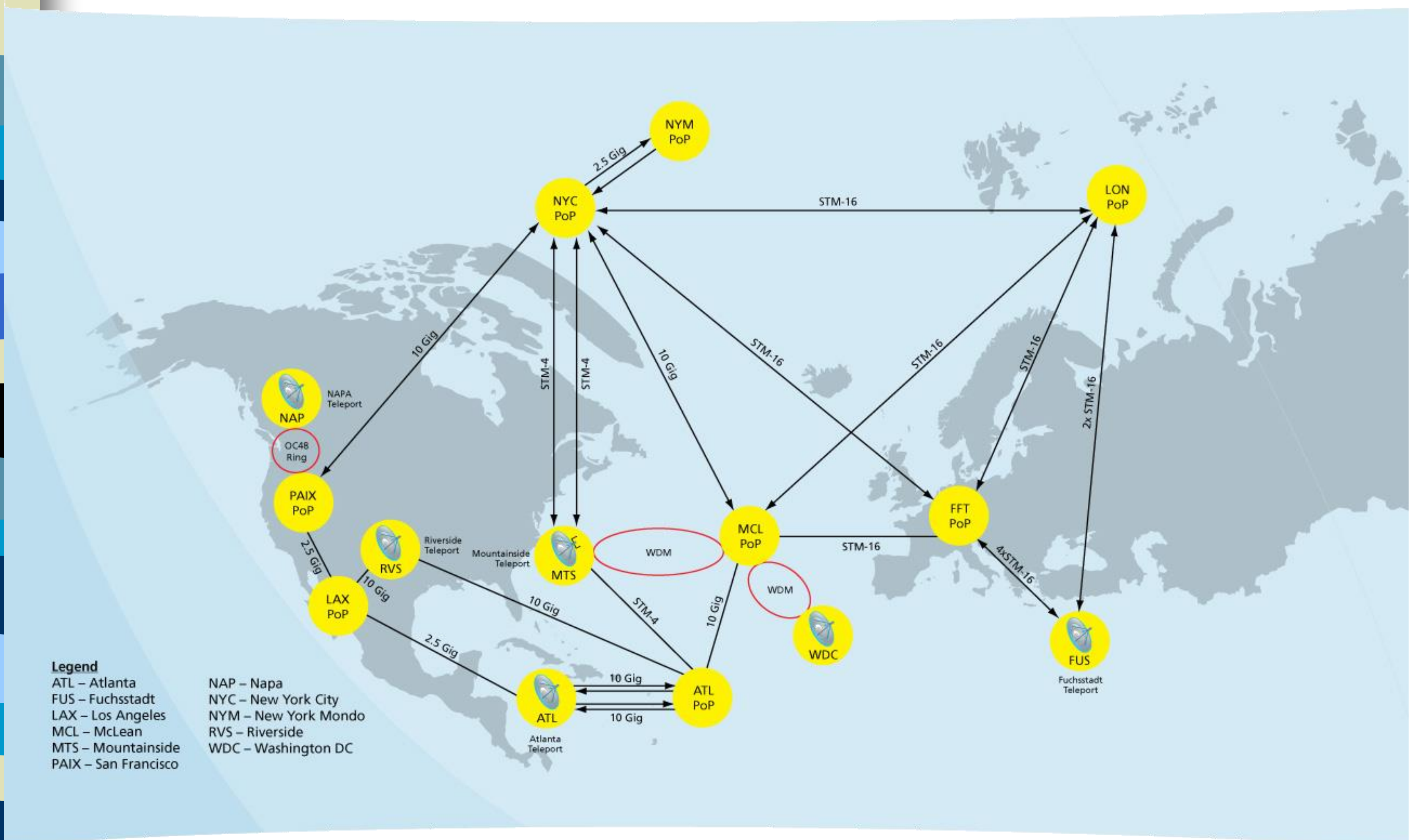



Tags
Readers
Local Software and Infrastructure
Enterprise Integration
Integration Platform
ERP
SCM
CRM
Local Server

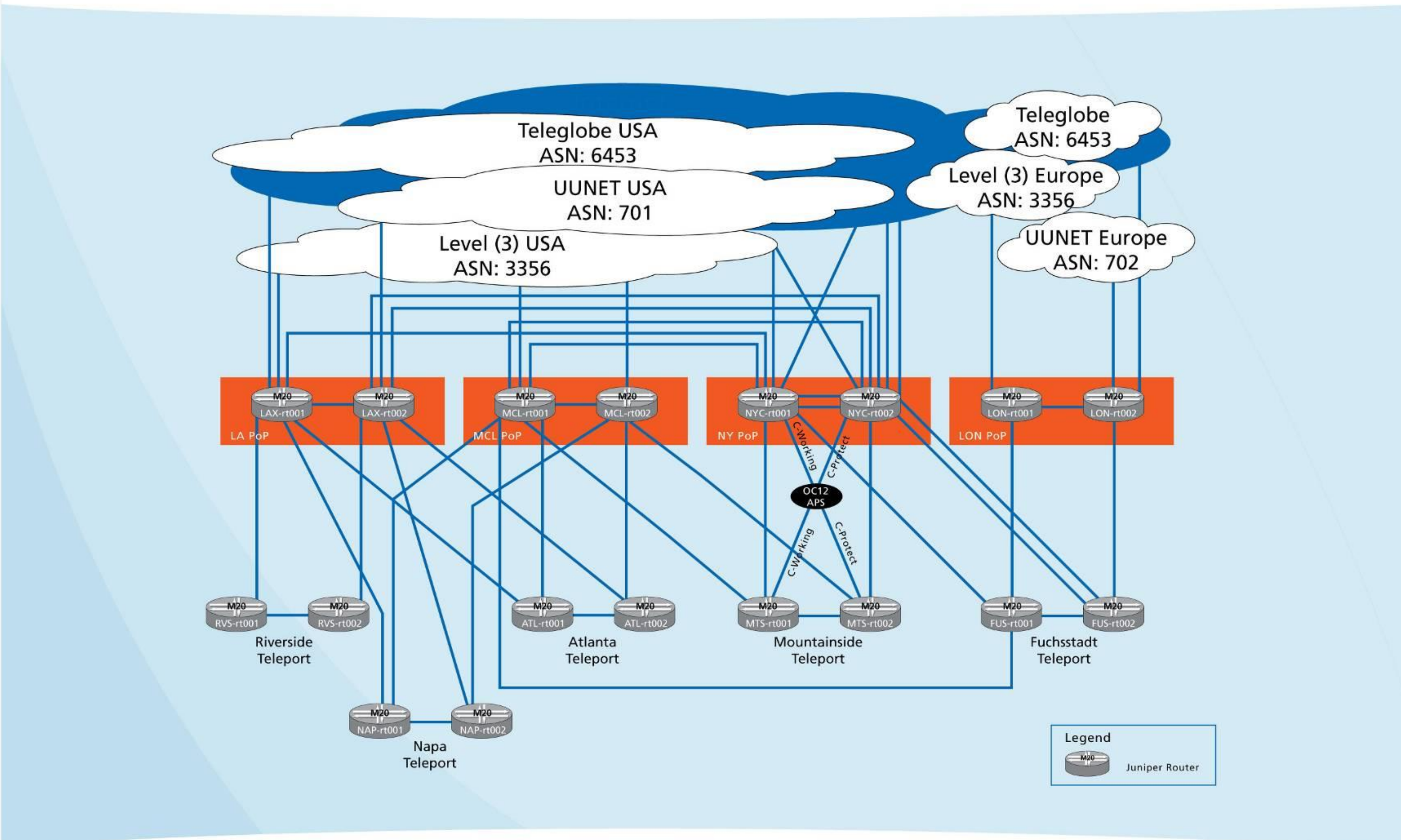
RFID



Intelsat GXS® Fiber Network



Intelsat GXS® IP Network



Cisco Catalyst 6500 Series Switches/Routers - Integration Technology for Security Systems

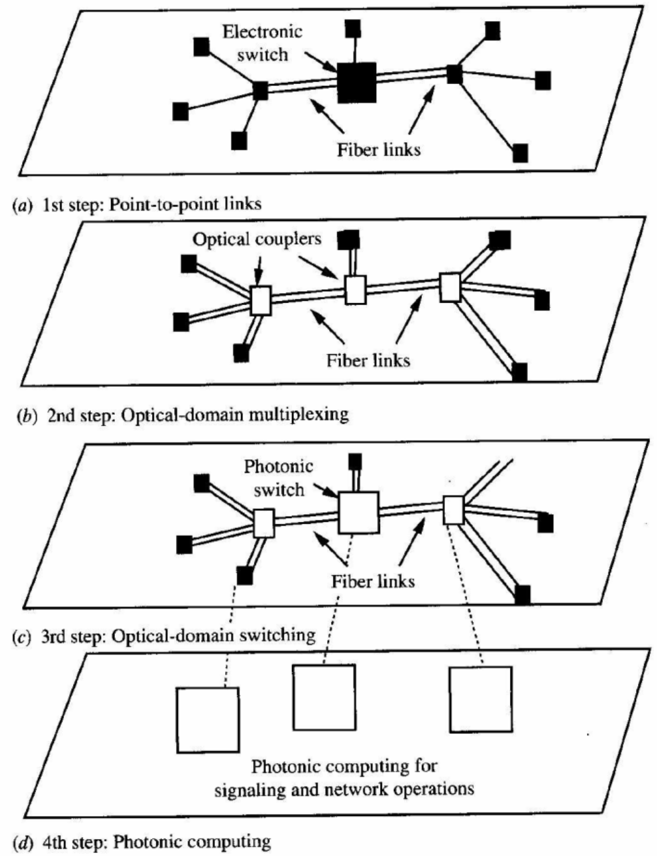
Evolution of All Optical Communication Network

a) Point to Point Links

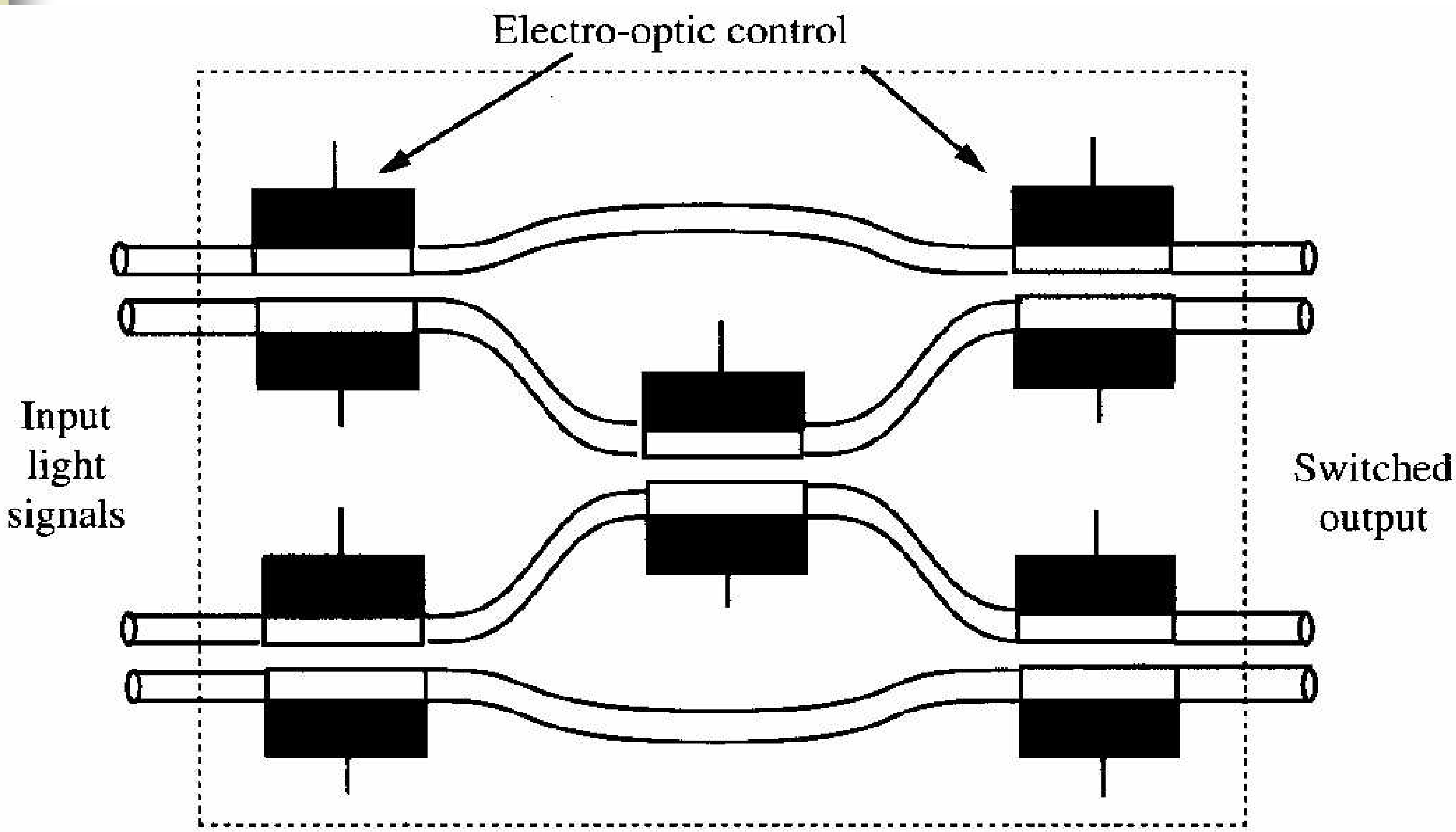
b) Optical domain multiplexing

c) Photonic switching

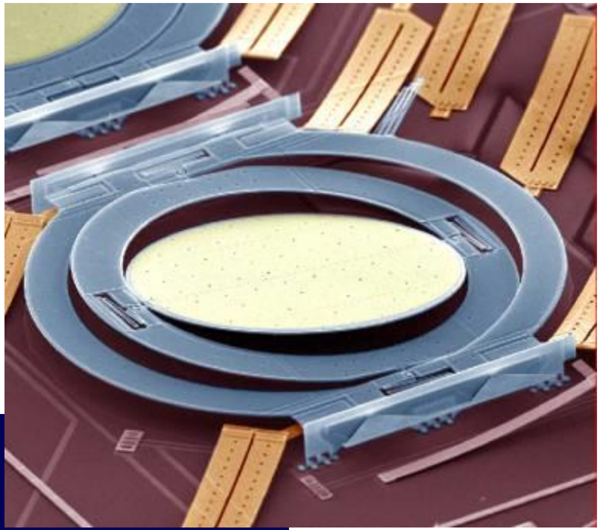
d) Photonic computing



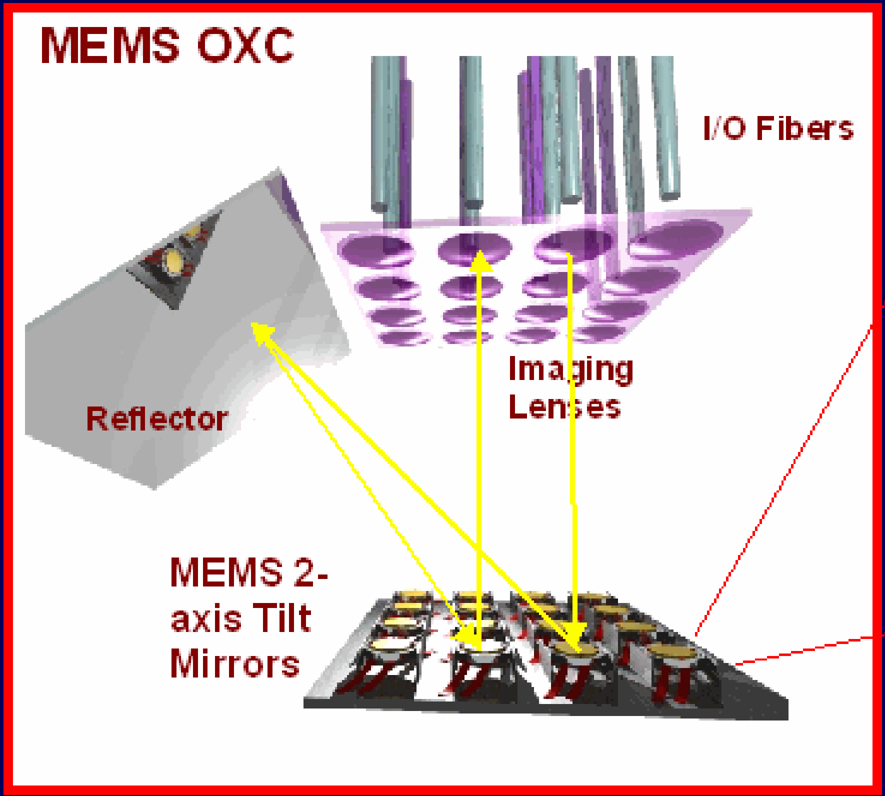
4 x 4 electro-optic photonic switch



MEMS Mirrors



Lucent MEMS OXC



MEMS DEVICE:
- 2-axis, angular range of > ±6°
- continuous, controlled tilt
- directly scalable to 256 mirrors (1024 in the long term)
- simple technology for rapid development / prototyping
- manufacturable

Glimmerglass Intelligent Optical Switch

System 600
32x32 - 192x192

• Handles all traffic data rates: 10GE up to OC-768 and 100GE

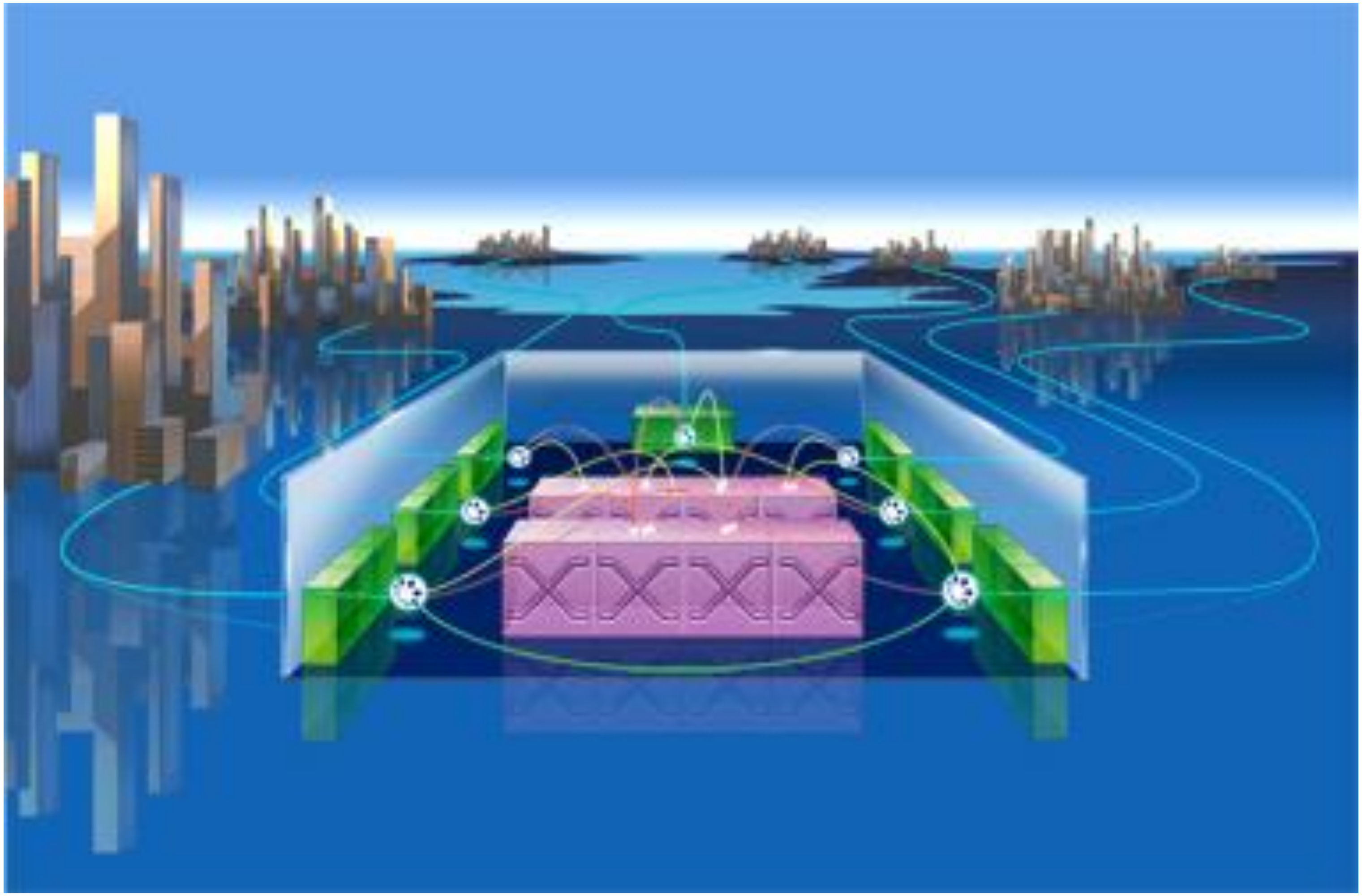
• Transparently accepts all signal formats: SONET/SDH, Ethernet, DWDM, digital, or analog

• Single-mode, wideband (1270 nm - 1630 nm)

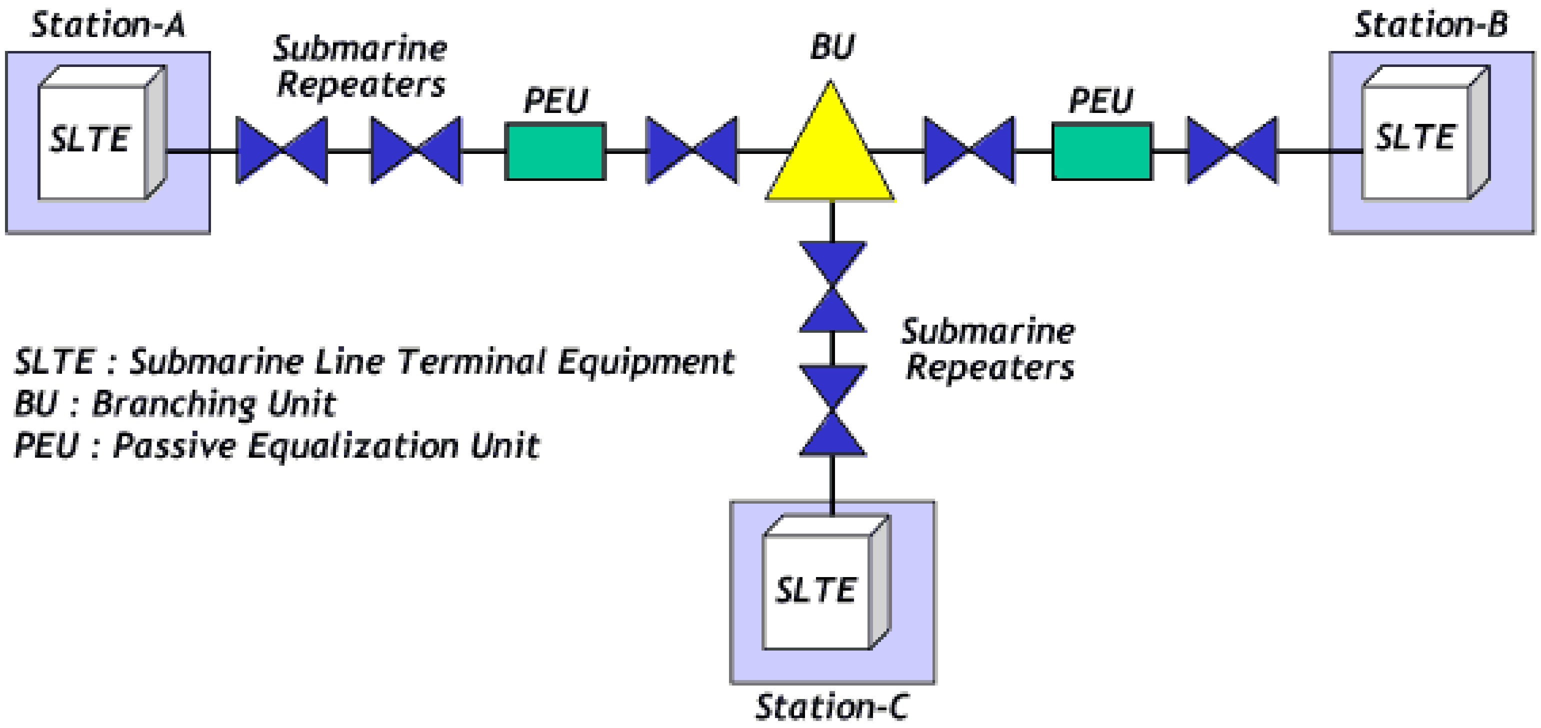
• 20 Millisecond switching

• Compact, low-power, high-density

Internet Peering Exchange via Optical Switching – Integration Technology



Submarine fibre optic cables



Optical Repeaters

Brand-new 980nm pump LD

Wide bandwidth of 36nm
Supporting 10Gb/s x 128 wavelengths

Maximum capability of 12FPs

Low noise figure of 5dB

Highly-reliable new 980nm pump LDs

Supervisory (SV) function of active Telecommand-Telemetry monitoring and passive C-OTDR
Digital supervisory and telemetry signals superimposed onto the optical traffic signal
Housed in a rugged, corrosion-resistant casing
Designed for 25 years of operation at depths down to 8,000m

Communication Systems

- An optical or lightwave communication system uses light waves as the carrier for transmission.
- Figure 2 shows a point to point communication system.
- When transmission links are interconnected with multiplexing or switching functions, figure (1), they are called a communication network.

Communication Network

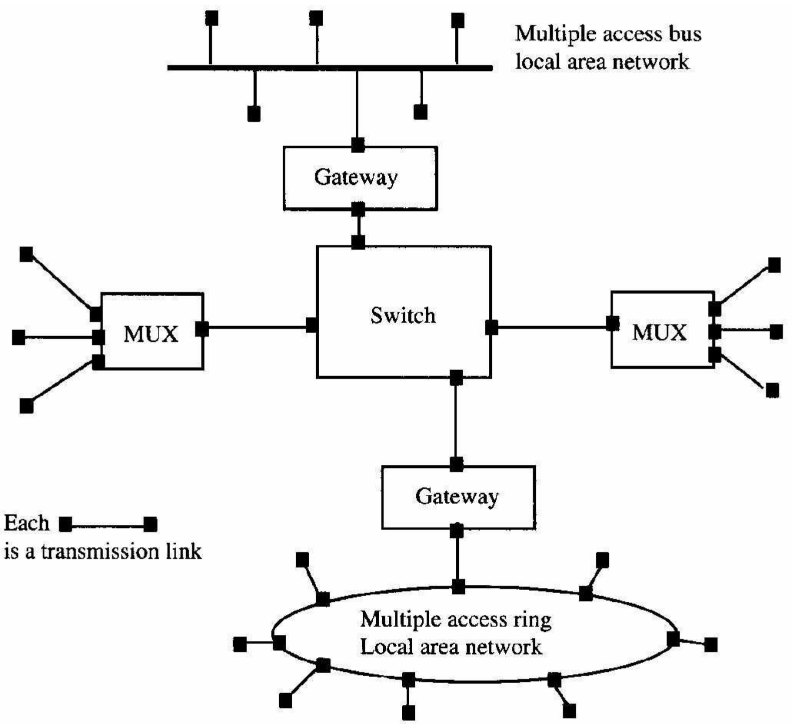


Figure 1 A communication network of interconnected links and subnetworks.

Communication Systems

- Each communication link shown in figure 1 consists of three basic components:
  - Transmitter
  - Channel
  - Receiver
- See Figure 2, with optical systems the channel noise is small but there is noise from the transmitter (light source) and the optical receiver

Point-to-Point Transmission Link

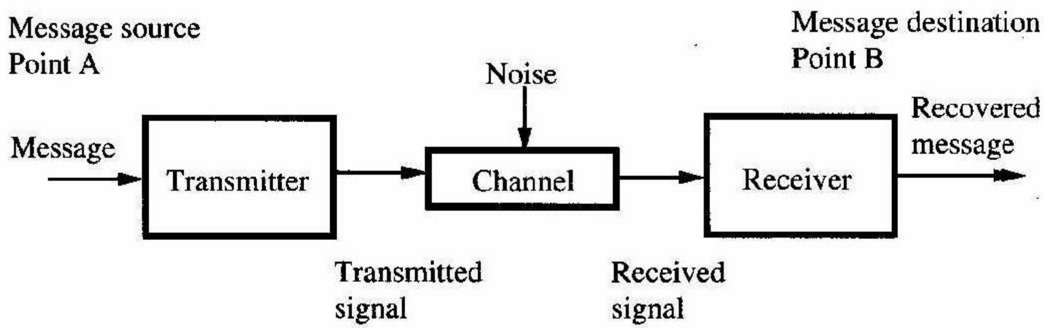


Figure 2 A point-to-point transmission link.

Transmitter and Receiver Blocks

- A Transmitter consists of blocks performing source coding, channel coding, line coding, modulation and signal amplification
- A receiver may include blocks performing equalisation, retiming, detection, demodulation and decoding; illustrated by figure 1.3

Communication System

Error Control

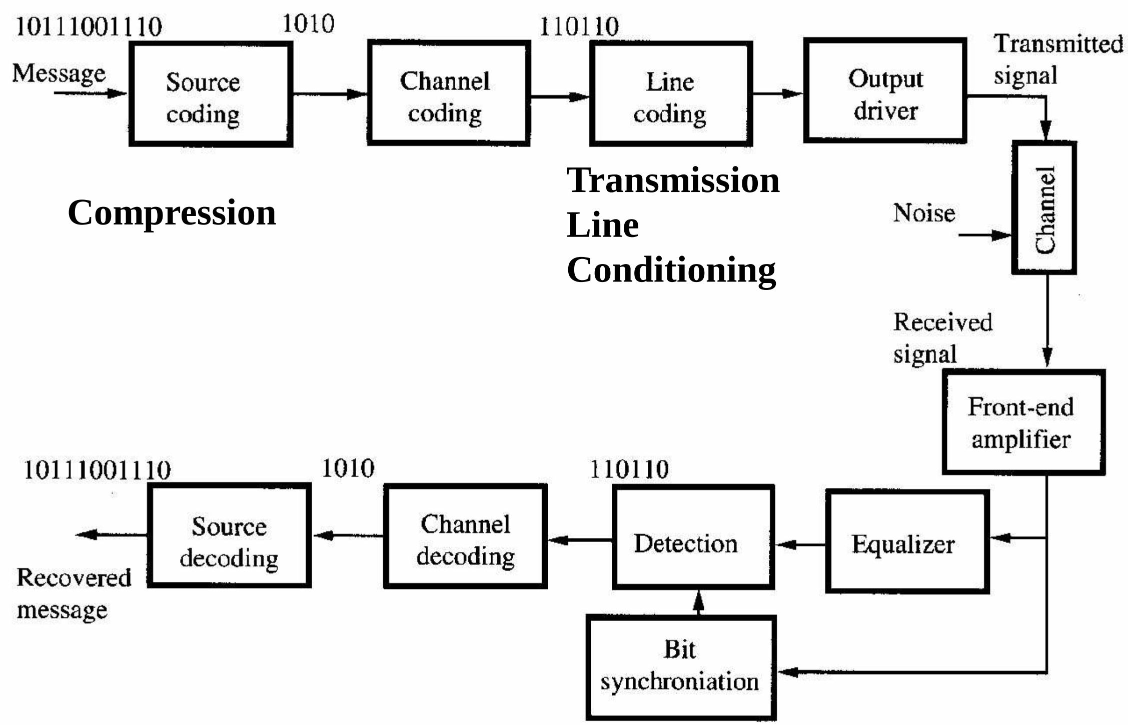


Figure 1.3 A more detailed look at a communication system.

Digitised Image Transmission

- Digitized image transmission consists of many bits eg 24 bits per pixel colour image of 1000 x 1000 pixels has 24 megabits or 3 megabytes of data
- Source coding is frequently used to reduce the number of bits in transmission. Because source coding is liable to transmission errors, channel coding is often used to detect and correct error bits by adding extra parity check bits
- In addition, line coding is used to achieve certain properties in the transmitted waveform, such as dc balance and sufficient transitions.

Digitised Image Reception

- At the receiver side, due to the added noise and distortion from transmission, an equalizer is used to maximise the detection performance.

- Bit timing synchronisation is used to recover the original transmitter bit clock for sampling and detecting the transmitted bits.

Transmission and Detection

- Differences in communication systems can be characterised in three ways:
- 1) Baseband versus passband
- 2) Analog versus digital
- 3) Coherent versus incoherent detection

Baseband versus Passband

- If the signal is transmitted over its original frequency band, the transmission is called baseband transmission
- If the signal is shifted to a frequency band higher than its original baseband, it is called passband transmission
- Some baseband and passband signals are illustrated in Figure 1.4

Baseband and Passband Signals

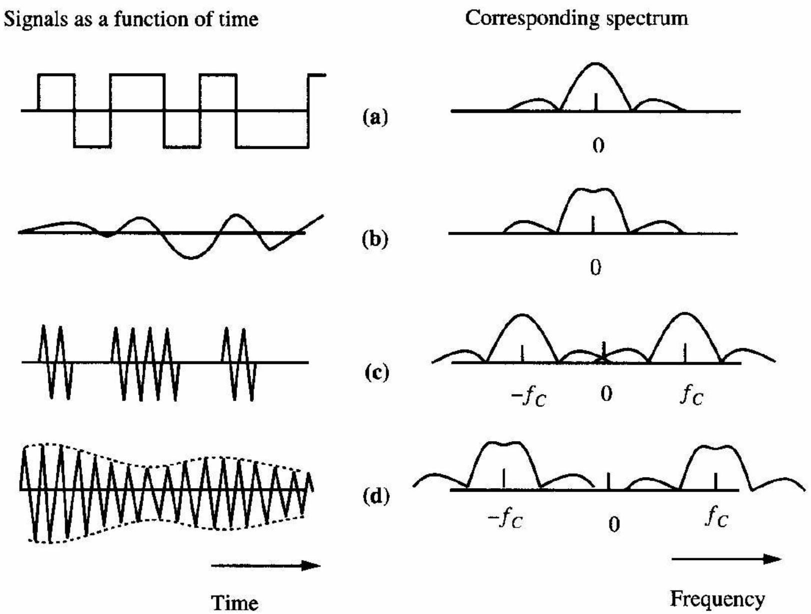


Figure 1.4 Illustration of baseband and passband signals: (*a*) a baseband binary signal, (*b*) a baseband continuous signal, (*c*) an amplitude modulated passband signal from the binary baseband signal, and (*d*) an amplitude modulated passband signal from the continuous baseband signal.

Passband

Shifting the baseband signal to a passband can be achieved by multiplying the baseband by a high frequency carrier.

Where *m(t)* is the baseband signal, $cos(w_c t)$ is the carrier and $S_{AM}(t)$ is called an amplitude modulated passband signal because its amplitude is proportional to the baseband signal, see figure 1.5

$$s_{AM}(t) = m(t)\cos(\omega_c t) \qquad \text{....1}$$

Amplitude Modulation

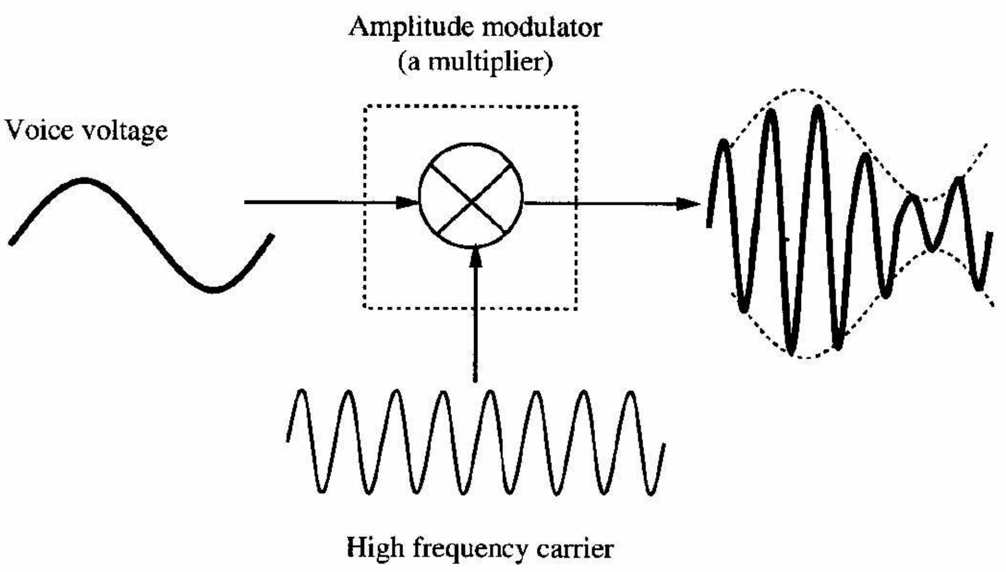


Figure 1.5 Illustration of amplitude modulation.

Fourier Transform

$$S_{AM}(\omega) = \mathcal{F}\{s_{AM}(t)\} = \frac{1}{2}M(\omega - \omega_c) + \frac{1}{2}M(\omega + \omega_c) \quad \ldots 2$$

This equation shows that the output spectrum consists of two frequency shifts of the baseband signal by an amount $\pm w_c$

The high frequency carrier can generally be expressed as:

$$c(t) = A\cos[\omega_c t + \phi(t)]. \qquad \ldots\ldots 3$$

Because it is a function of not only amplitude *A* but also its phase $\phi(t)$ and frequency $w_c/2\pi$, another way to shift a baseband signal to a passband signal is to modulate the phase or frequency according to the baseband signal

Frequency Modulation

- In FM the instantaneous frequency of the carrier *f(t)* is the sum of the fixed high frequency term f_c plus a small term proportional to the baseband signal. That is, an FM signal of the form:

$$s_{FM}(t) = A\cos[\theta(t)] \qquad \ldots..4$$

has instantaneous frequency

$$f(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} = f_c + \frac{k_{FM}}{2\pi}m(t) \qquad \ldots..5$$

Frequency Modulation

- Where the instantaneous frequency is by definition the time derivative of the phase divided by 2π, and k_{FM} is called the modulation index.
- In contrast with AM signals, the amplitude or the envelope A of an FM signal is constant, but its instantaneous frequency moves up and down around f_c
- The amount of frequency deviation is determined by both the modulation index and input message signal.

Why Passband?

- Some transmission media have either a large loss or high noise at low frequencies; for example, optical fibres have a cutoff frequency below which electromagnetic waves have a high loss
- Therefore, we need to convert a baseband signal to a lightwave for transmission over optical fibres

Why Passband?

- Another reason for passband transmission is to multiplex multiple signals into the same transmission medium.
- For example, AM/FM radio and TV channels are multiplexed in the frequency domain by a process called frequency division multiplexing (FDM), where each channel is centred around a pre-assigned carrier frequency.
- AM, FM, and TV are in the frequency ranges of 530-1700 kHz, 88-108 MHz, and 54-88 MHz plus 120-600 MHz, respectively

Why Passband?

- In optical communications, the carrier is in the visible or infrared frequency range
- If the amplitude of a light signal is proportional to a baseband signal, the amplitude modulation is similar to that in AM/FM radio
- As in radio, one can multiplex several optical signals of different carrier frequencies into the same fibre
- Multiplexing in the frequency domain allows multiple transmissions at the same time
- This same FDM technique in optical communications is called wavelength division multiplexing (WDM)

Sub-carrier Multiplexing

- FDM is frequently done in several hierarchical layers. This is called sub-carrier multiplexing (SCM).
- In the case of optical communications, the first step of frequency multiplexing is in the radio frequency (RF) domain. The combined radio signal is used to modulate a light carrier.

Video transmission over optical fibres

- Cable TV signals are traditionally amplitude modulated and frequency multiplexed over the 54-600 MHz band
- As optical fibre transmission has become more cost effective, many cable operators have used video transmission over fibres in video signal distribution
- To transmit these analogue video signals that have already been multiplexed in the RF domain, SCM is a natural choice.

Video transmission over optical fibres

- In this approach the multiplexed RF signal directly modulates the output light intensity of a laser diode
- This sub-carrier modulation is illustrated in figure 1.6
- There are two carrier shifts, the first carrier shift is from the baseband to the RF band, and the second is from the RF band to the optical band

Sub-carrier Multiplexing

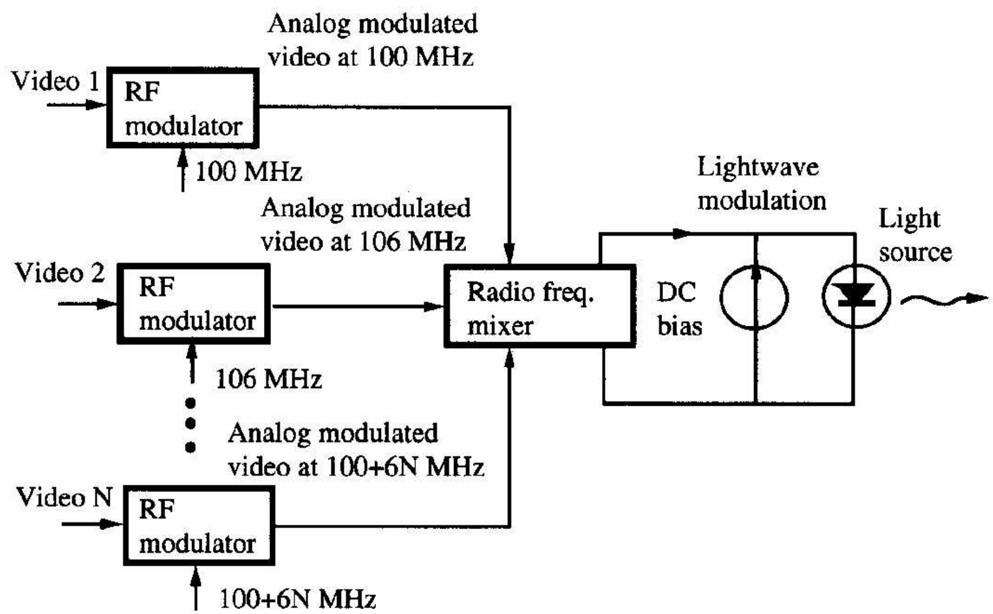


Figure 1.6 Illustration of subcarrier multiplexing for cable TV signals. Carrier frequencies shown are not the same as those used in real systems.

Optical Bandwidth

- Figure 1.7 shows that lightwaves are five to six decades higher than microwaves in frequency
- Each decade is 10 times higher in frequency, which is the fundamental reason for a large transmission capacity in optical communications – several THz or thousands of GHz

Electromagnetic Spectrum

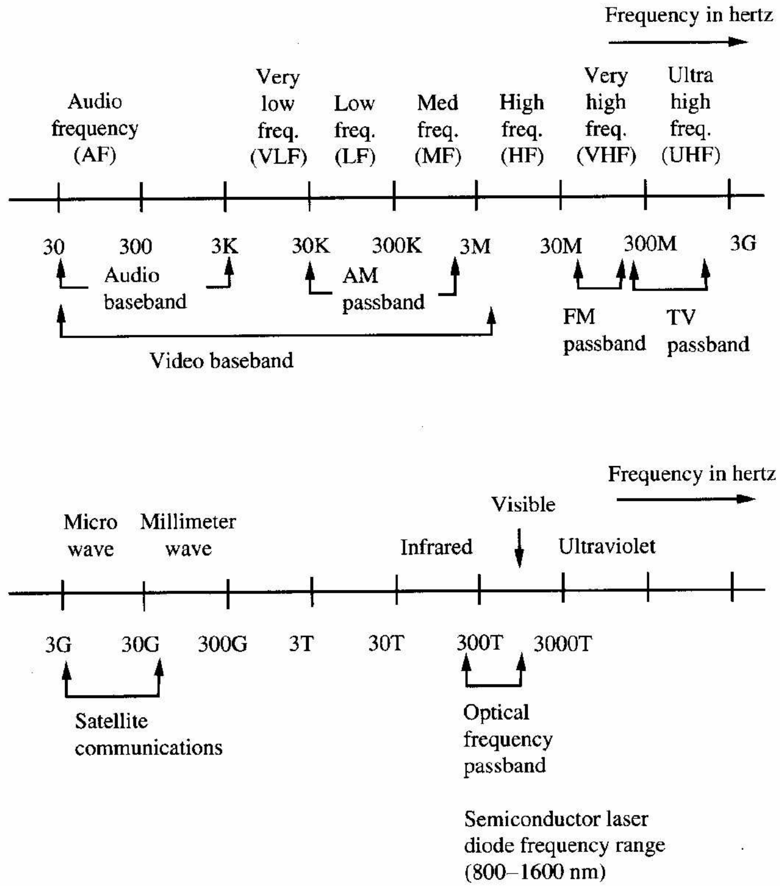


Figure 1.7 Electromagnetic spectrum from dc to lightwaves.

Analogue versus Digital

- An important characteristic in communications is the discreteness of a message that is transmitted
- A digitized image is transmitted in discrete binary bits – two levels – This is called digital communication
- However, in the previous AM and FM examples, input signals have a continuous waveform, this is called analogue communication

Analogue versus Digital

- Because a digital signal only has a finite number of discrete levels, digital communication is in general more immune to noise than analogue communication
- For example, if noise in the channel is relatively small compared to the distance between two adjacent levels, original messages can be recovered correctly in the presence of noise

Analogue versus Digital

- However, in analogue communication, once noise is added to the transmitted signal, it cannot be easily removed
- This noise effect can accumulate when several analogue transmission links are cascaded
- Because of this noise effect many analogue communication systems have been converted to digital
- Most voice transmissions in current telephone networks are now digital

Amplitude-shift keying (ASK)

- When the input to the AM modulator in equation 1 is not continuous but instead has a finite number of discrete values, we have the digital counterpart of amplitude modulation called amplitude-shift keying (ASK)
- A four level ASK signal is illustrated in figure 1.8
- It can be seen that it is a passband digital signal, although only one carrier cycle per bit interval is drawn for illustration

Amplitude-Shift Keying (ASK)

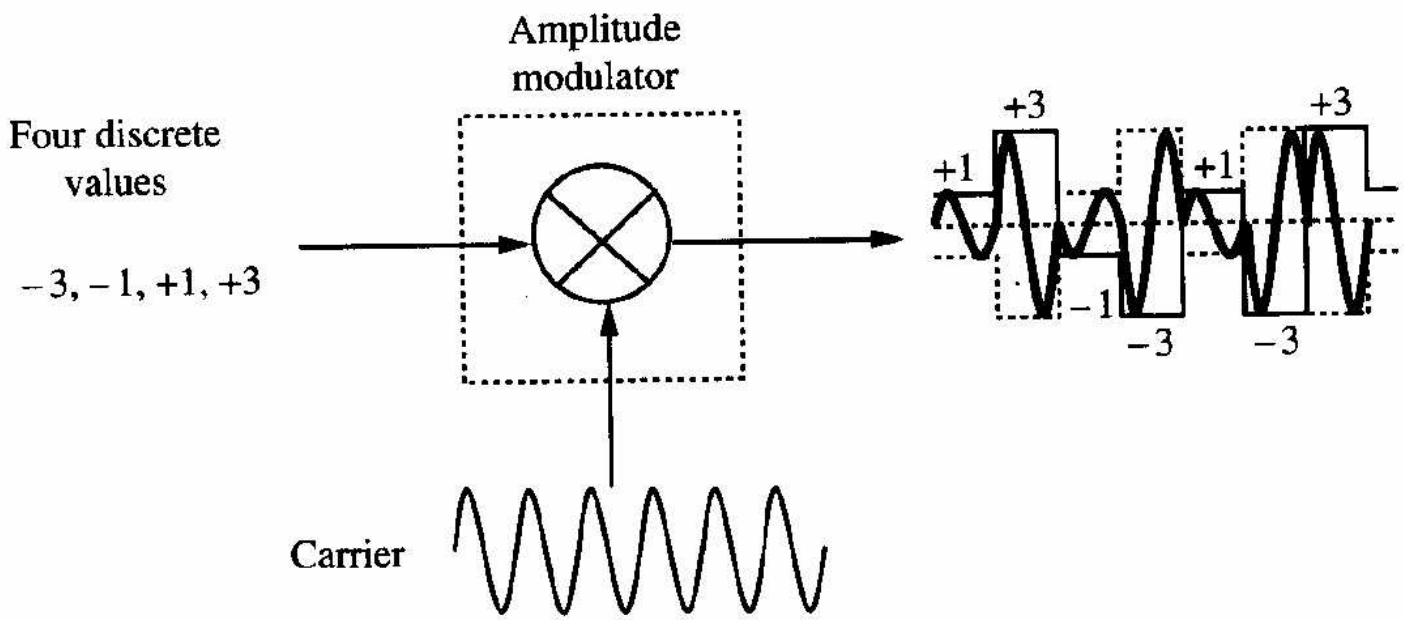


Figure 1.8 Illustration of four-level ASK signal.

U-Interface of ISDN

- A baseband version of the four level amplitude modulated signal is used in the U-interface of the integrated services digital networks (ISDN)
- The U-interface is the user interface between the ISDN network and its subscribers
- In this defined interface, the bit rate is 160kb/s, including 144kb/s for user data and 16 kb/s for framing and control
- Because of the 4 levels, each symbol carries two information bits, hence the baud rate is 80 kilobauds per second

Advantage of Digital Communication

- In analogue communication, if the transmitted signal power is 0.1 mW and the noise power in the channel is 1 microwatt, the SNR is 100
- In binary digital transmission, a SNR of 100 can have a bit error detection probability lower than 10^{-22}
- This implies that on average there is fewer than one bit in error if we transmit 10^{22} bits
- Therefore the ratio of the number of correct transmitted bits to that of the error bits is 10^{22}, much higher than the SNR of 100

Trade off

- The trade-off for better transmission quality in digital communication is a larger transmission bandwidth
- For example, a 3kHz voice signal sampled at an 8kHz rate and quantized at 8 bits per sample requires a 64 kHz bandwidth in digital transmission, and 6MHz video can require 45 MHz with moderate compression

Coherent versus Incoherent Detection

- When a transmitted signal is received, we need to detect what was originally transmitted
- If the signal is passband, it must be shifted back to the baseband
- There are two different ways to do this: coherent or incoherent detection

Coherent versus Incoherent Detection

- In coherent detection, a different carrier source at the receiver side is used to demodulate the received signal or to shift the passband signal back to the baseband
- This carrier is generally called the local carrier and is synchronised to the received signal in frequency and phase
- In incoherent detection, there is no use of the local carrier. Instead some nonlinear processing is used to extract the amplitude or envelope of the passband signal

Coherent Detection

- In AM transmission, let the transmitted signal be of the form given in equation (1).

$$s_{AM}(t) = m(t)\cos(\omega_c t) \qquad \text{....1}$$

- If we can recover the same carrier, w_c, at the receiver, we can simply recover the original message signal by multiplying the received signal by the same carrier and passing the product through a low pass filter

Coherent Detection

- Hence, *m(t)*, can be recovered from the low frequency part of :

$$s_{AM}(t)\cos(\omega_c t) = \frac{1}{2}[m(t) + m(t)\cos(2\omega_c t)] \ldots\ldots 6$$

Using: $\cos^2 A = \frac{1}{2} + \frac{1}{2}\cos 2A$

Incoherent Detection

- For an AM signal, where k_{AM} is the modulation index such that $|k_{AM}\, m(t)|$ is always smaller than 1

$$s_{AM}(t) = [1 + k_{AM} m(t)] \cos(\omega_c t) \qquad \ldots\ldots.7$$

By taking the square of this AM signal, we have:

$$s_{AM}(t)^2 = k_{AM} m(t) + \frac{1}{2} + \frac{1}{2}[k_{AM} m(t)]^2 + \frac{1}{2}[1 + k_{AM} m(t)]^2 \cos(2\omega_c t).$$

$$\ldots\ldots\ldots..8$$

Incoherent Detection

$$s_{AM}(t)^2 = k_{AM}m(t) + \frac{1}{2} + \frac{1}{2}[k_{AM}m(t)]^2 + \frac{1}{2}[1 + k_{AM}m(t)]^2 \cos(2\omega_c t). \quad \text{.............8}$$

- The first term is the desirable signal with a proportional constant k_{AM}.The second term is the dc term and is not important. The third term can be neglected if k_{AM} is small enough. The last term is a high frequency term and can be eliminated by low-pass filtering
- This is called **envelope detection** and is incoherent because no local carrier is used

Coherent versus Incoherent Detection

- The primary trade-off between coherent and incoherent detection is implementation complexity versus detection performance
- Coherent detection requires a local carrier and associated carrier recovery; furthermore, the carrier source must be single frequency
- In incoherent detection we suffer distortion and limited signal power (small k_{AM}) in exchange for detection simplicity
- In optical communications, most systems use incoherent detection for implementation simplicity at high speeds

Photon Counting

- In on-off-keying (OOK) optical communications, the light source in the transmitter is turned on if the input binary bit is “1” and turned off if it is “0”
- At the receiver, we can simply use a photodiode that converts received photons into photocurrent
- With this scheme a local optical carrier is unnecessary

Quantum Limit

- The quantum limit is the theoretical lower limit on the average signal energy needed to achieve a specified bit error rate (BER) in digital communication
- For example, the quantum limit is 10 photons per bit to get a BER of 10^{-9} , in practice we need a few hundred photons
- If coherent detection is used, the required number of photons can be much closer to the quantum limit

Modulation and Line Coding

- Similar to modulation that converts a baseband signal to a passband signal, line coding converts a binary input sequence into a suitable waveform for transmission. Because of similar functions line codes are also called modulation codes
- In general modulation can be used in both digital and analogue communications
- Line coding maps a finite set of signals to another set of signals with certain properties such as dc balance or frequent transitions

Communication System

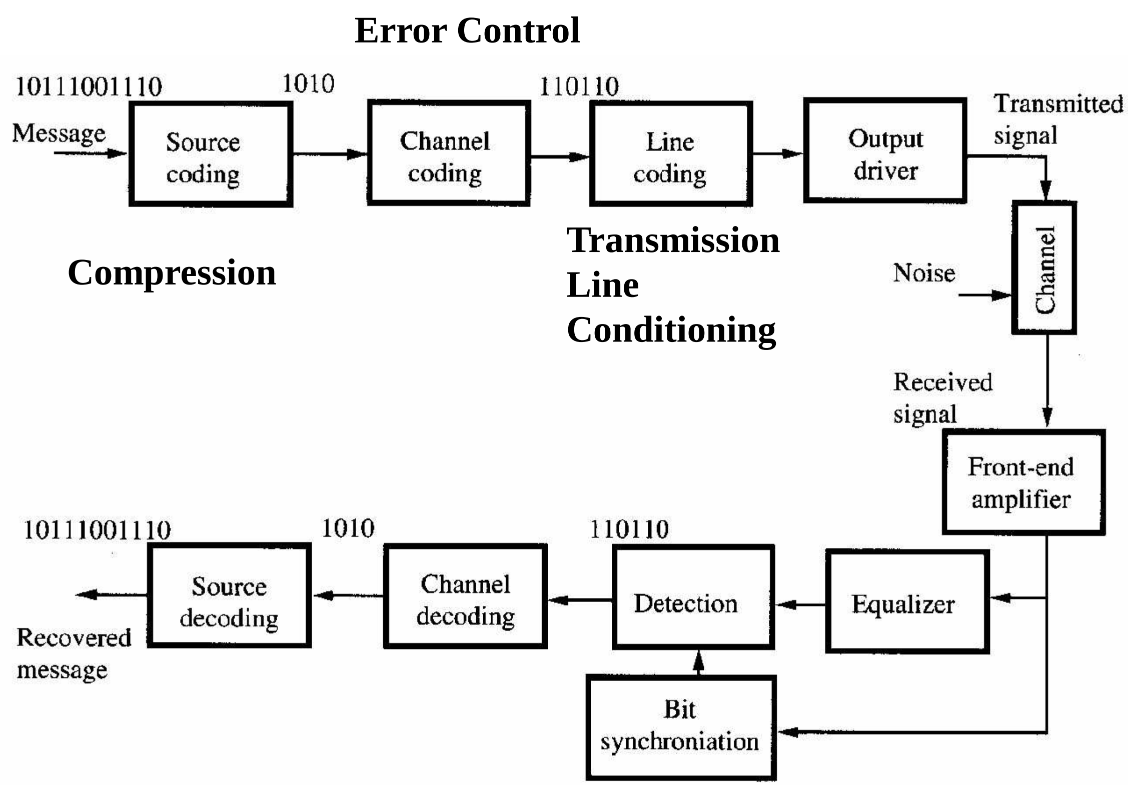


Figure 1.3 A more detailed look at a communication system.

Modulation and Line Coding

- Line coding is always used in digital communications, whether baseband or passband
- In addition to modulating the amplitude or frequency of a carrier, we can modulate the phase of the carrier
- A phase modulation (PM) signal has the following general form:

$$s_{PM}(t) = A\cos[\omega_c t + k_{PM} m(t)] \qquad \ldots\ldots\ldots 9$$

Modulation Schemes

$$s_{PM}(t) = A\cos[\omega_c t + k_{PM} m(t)] \quad \ldots\ldots\ldots\ldots 9$$

- Where w_c is the central carrier frequency, k_{PM} is the PM modulation index and *m(t)* is the modulation signal or information
- If the baseband signal in equations (1), (7) and (9) is discrete and has M different levels, ±1, ±2, ±3, ±(M-1)
- We have the corresponding different counterparts called M-level ASK (amplitude shift keying), FSK (frequency shift keying), and PSK (phase shift keying)

RZ and NRZ Line Codes

- Two of the simplest and most common line codes are the return-to-zero (RZ) and non-return-to-zero (NRZ) codes
- These two codes are illustrated in figure (1.9)
- These two codes transform binary bits, 1’s and 0’s, into pulses of different durations
- RZ is better than NRZ from the time recovery consideration
- For instance if there is a long sequence of 1’s,the transmitted NRZ signal is constant. This constant signal makes it difficult for the receiver to detect how many bits are transmitted

Return-to-Zero & Non-return-to-zero Line Codes

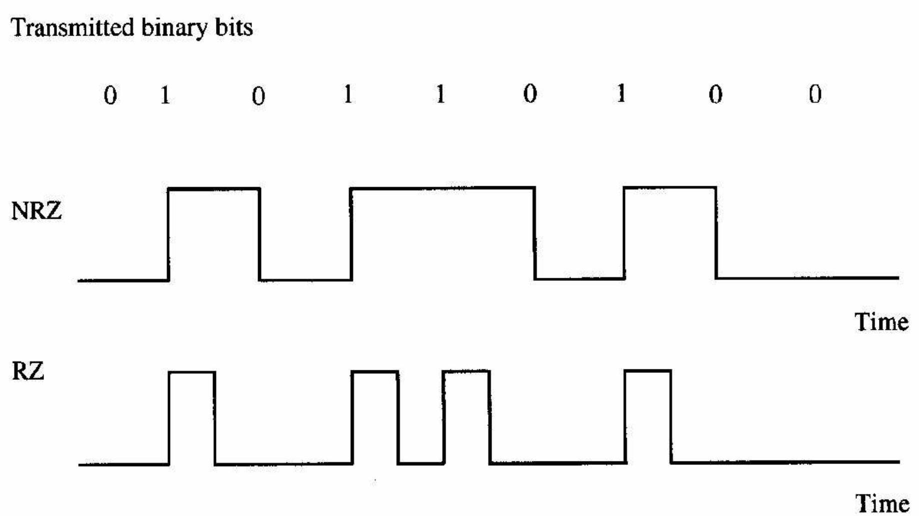


Figure 1.9 RZ and NRZ line codes.

RZ and NRZ Line Codes

- If RZ is used, the transmitted signal is a periodic pulse train.
- The period equals the bit interval, therefore, it easy for the receiver to detect the transmitted bits
- RZ signaling can be considered a special case of amplitude modulation where the carrier frequency is set equal to the bit rate

Return-to-Zero & Non-return-to-zero Line Codes

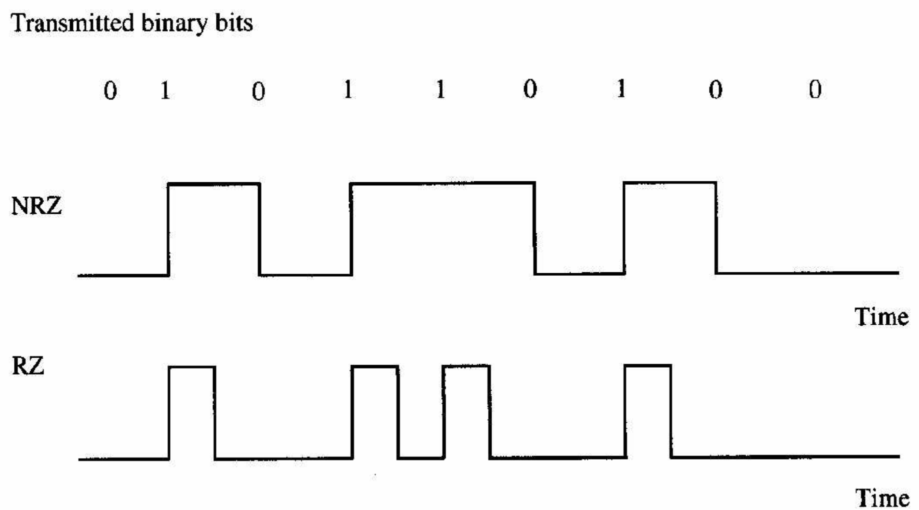


Figure 1.9 RZ and NRZ line codes.

Advantages of Optical Communications

- Large transmission capacity: the signals are carried by high frequency carriers and WDM is used. Capacity is several thousand GHz
- Low loss: fibre attenuation can be as low as 0.2dB/km at a wavelength of 1.55 microns. If only loss is considered, optical fibres can transmit signals 5 times further than waveguides and 50 times further than twisted-pair wires

Advantages of Optical Communications

- Immunity to Interference: because of the waveguide nature and easy isolation, optical signals can be easily confined in a fibre without interference. Twisted pair and radio transmissions have significant crosstalk and multi-path interference
- High-speed interconnections: optical communication is well suited for high speed interconnections. Unlike electrical signals, which require careful control of impedance matching

Advantages of Optical Communications

- Parallel transmission: because optical signals can be transmitted in free space, parallel transmission in three dimensions is possible. This provides powerful ways to interconnect large numbers of processors for parallel processing, photonic switching and optical computing

Components in Optical Comms

- There are three basic components in every optical fibre communication system: light source, optical fibres, light detector
- In addition to these three key components other components include:
  - Optical couplers and splitters to combine and separate optical signals
  - Optical filters such as Fabry-Perot resonators to select optical signals at a particular frequency
  - Photonic switches for switching optical signals
  - Isolators to avoid undesirable reflections
  - Polarisers to maintain the light polarisation
  - External modulators to modulate the phase or amplitude of a light carrier

Components in Optical Comms

- Figure 1.10 illustrates the use of these components in a photonic WDM switching network
- Each laser diode in the transmitter is operated at a different carrier frequency
- They are combined via an optical coupler
- The combined signal is sent to splitter by an optical fibre
- The splitter directs the received signal to each of the optical filters
- Each filter is a passband filter at a selected optical frequency

Optical Communication Components

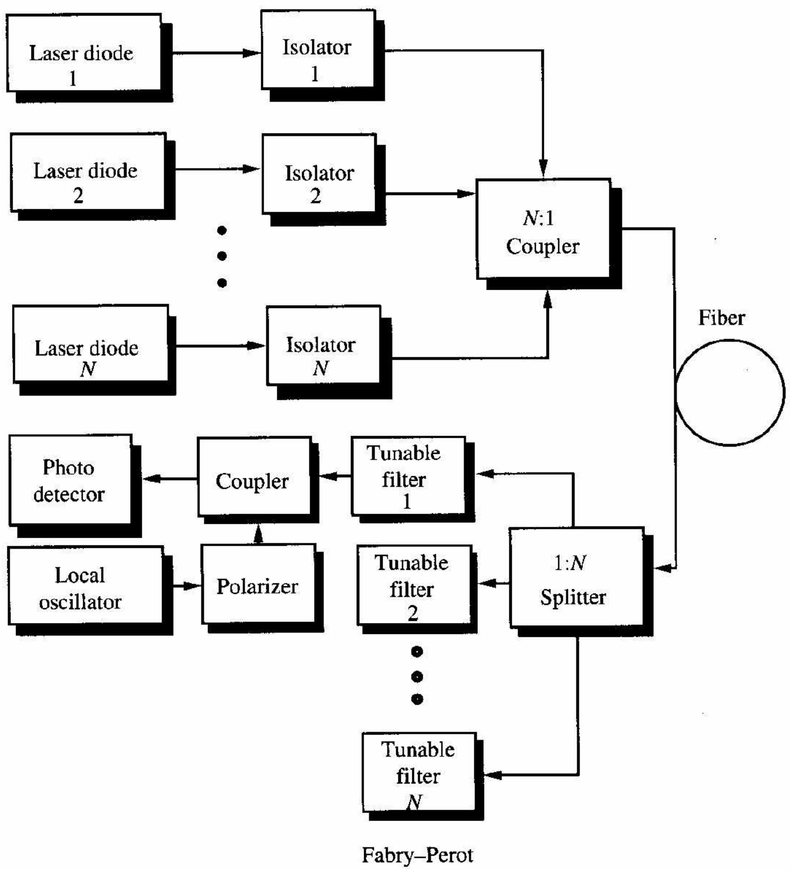


Figure 1.10 Illustration of optical communication components.

Components in Optical Comms

- Therefore, each signal on the transmitted side can be routed to any detector on the receiving side
- Therefore this system performs photonic switching
- The received signal is coherently detected at the receiver where a polariser aligns the polarisation between the received signal and the local oscillator signal

Optical Communication Components

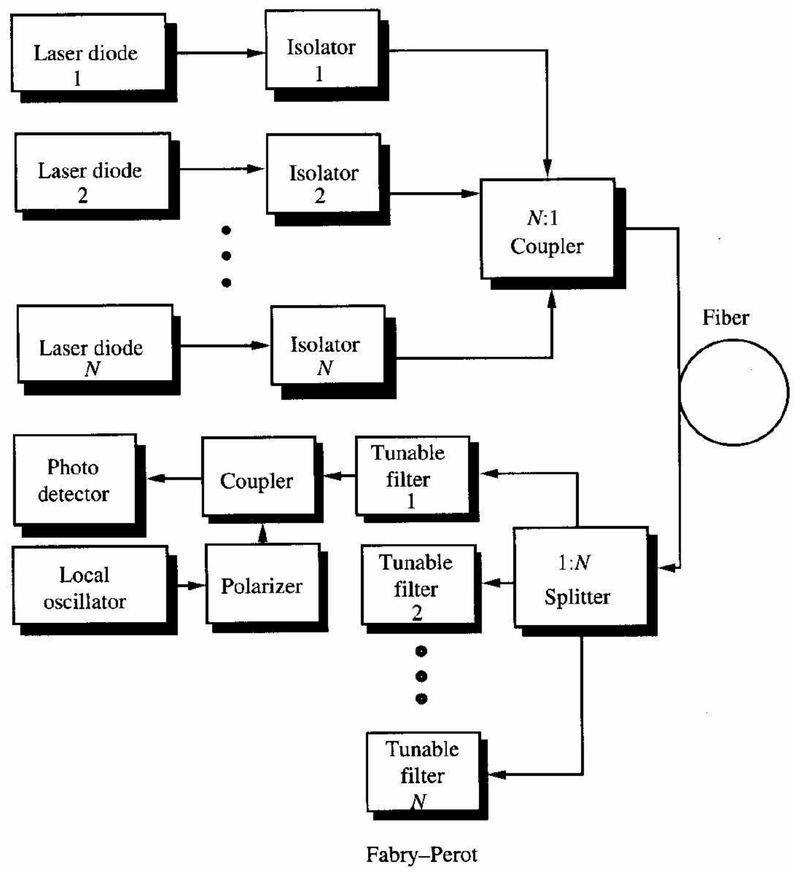


Figure 1.10 Illustration of optical communication components.

Advances in Optical Comms and System Applications

- To improve the capacity-distance product, higher output power and smaller fibre attenuation are essential to longer transmission distance and good spectral coherence is key to higher transmission speeds
- Therefore most effort has been made to:
  – improve the output power and spectral coherence of light sources
  – reduce fibre attenuation and dispersion

Technological Advances

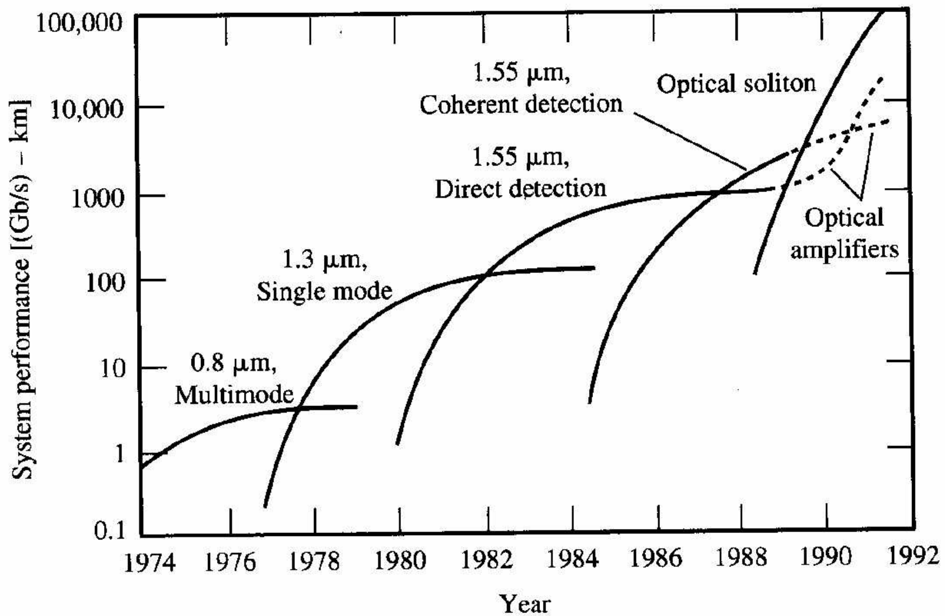


Figure 1.11 Advances of lightwave technology over the last two decades. As illustrated, the technology has developed through five generations, with each newer generation reaching a higher capacity–distance plateau.

Light Source Coherence

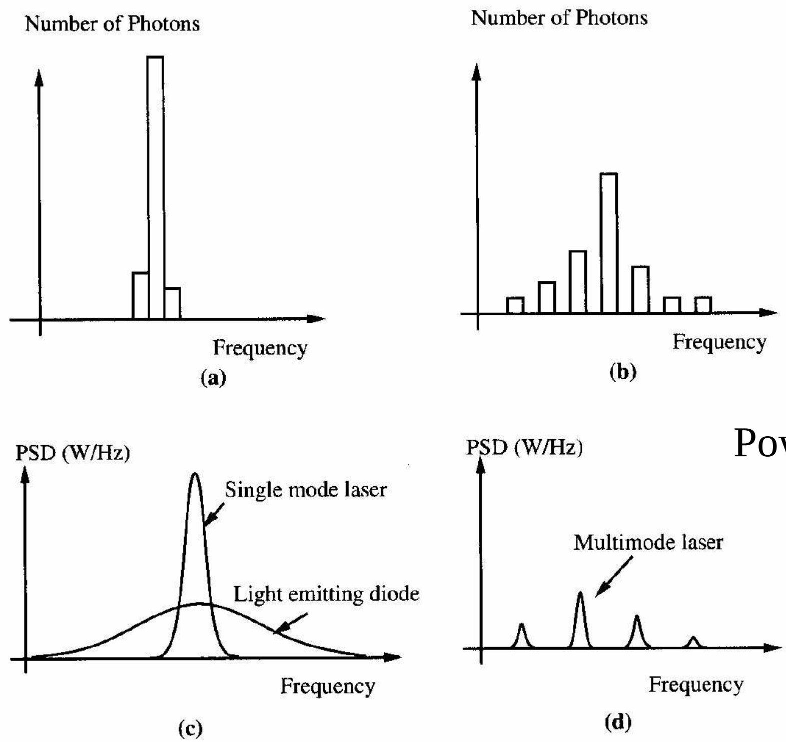
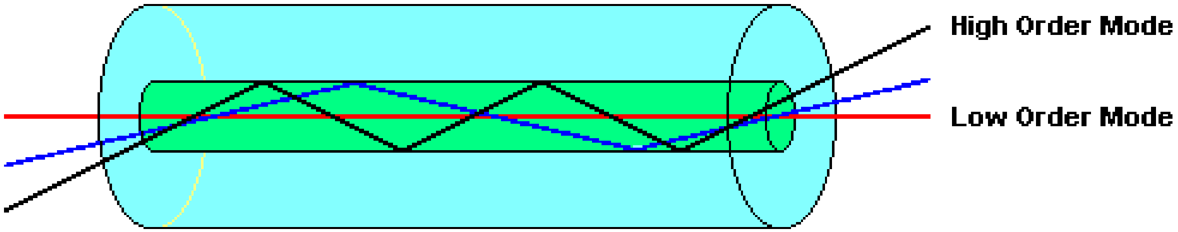
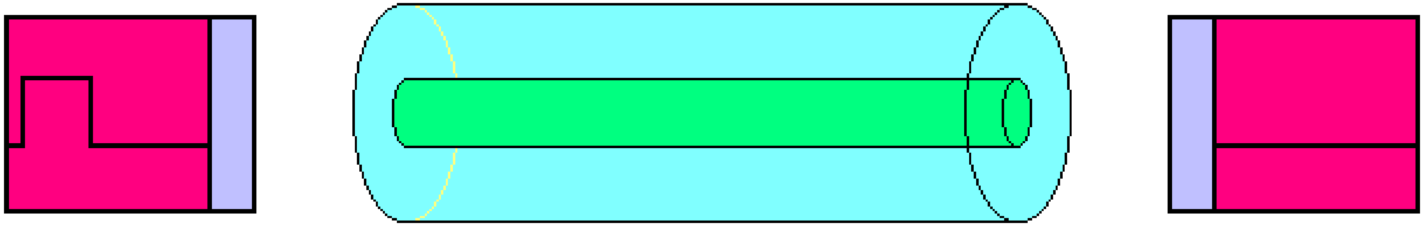


Figure 1.12 Illustration of coherence of a light source output: (*a*) a photon histogram of high coherence, (*b*) a photon histogram of low coherence, (*c*) PSDs of a typical single-frequency laser diode and a light emitting diode, and (*d*) PSD of a multimode laser diode.

Power spectral density (PSD)

Problems to be avoided





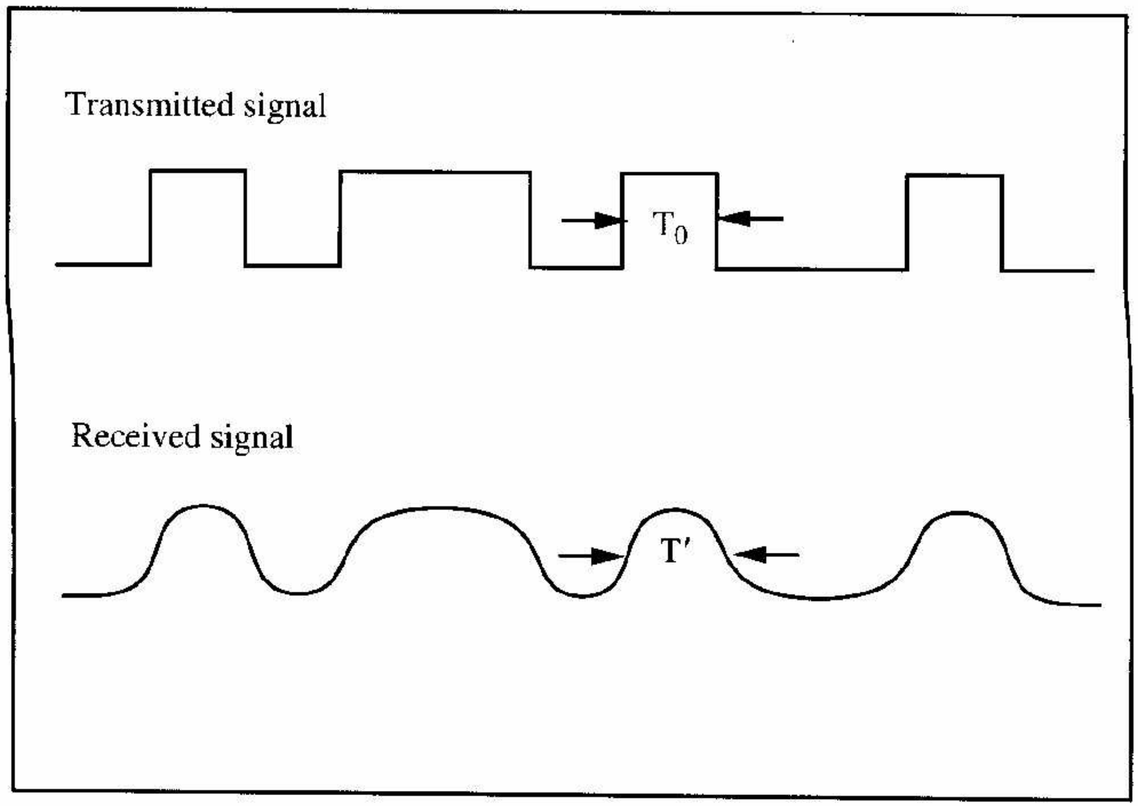


Figure 4.14 Transmitted and received optical pulses.

Five Generations of Lightwave Technology

Table 1.2 Summary of the five generations of lightwave technology development.

Generation	Light Sources	Wavelength (nm)	Fiber Attenuation (dB/km)	Fiber Dispersion	Detection
First	GaAs LED and FP LD	800–900	>5	Large	Incoherent
Second	III–V FP LD	1300	1 at 1330 nm	Minimal at 1300 nm	Incoherent
Third	III–V DFB LD	1300 and 1550	0.2 at 1550 nm	Minimal at 1300 nm	Incoherent
Fourth	III–V DFB and DBR LD	1300 and 1550	0.2 at 1550 nm 0.5 at 1300 nm	Dispersion shifted fiber for zero dispersion at 1550 nm	Coherent
Fifth	III–V DFB and DBR LD	1300 and 1550	Optical amplifiers	Optical solitons	Incoherent and coherent

NOTE: FP stands for Fabry–Perot type lasers, DFB stands for distributed feedback lasers, and DBR stands for distributed Bragg reflector lasers. DFB and DBR are single-frequency lasers.

First Generation

- In the first generation, multimode fibres (MMF) and direct bandgap GaAs semiconductors were used.
- Multimode fibres allow multiple propagation modes that result in large modal dispersion
- GaAs devices operate at the 800-900nm wavelength range in which fibres do not have the lowest attenuation (> 5dB/km) or dispersion
- Therefore , both transmission distance and speed were limited in the first generation

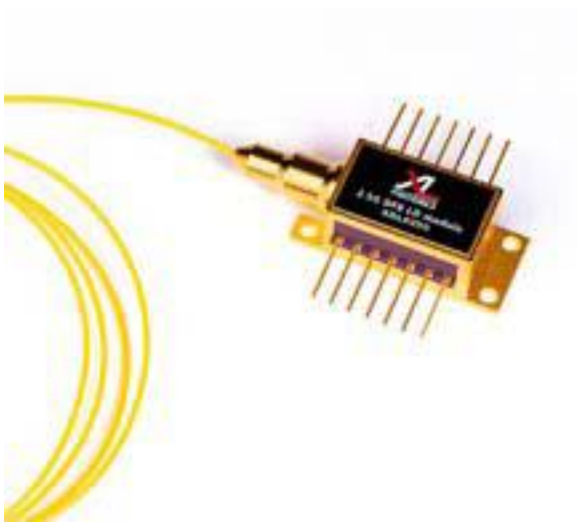
Second Generation

- As fibre and material technology advanced, single mode fibres (SMF) and other III-V compound semiconductors were used in the second generation
- Single mode fibres have much smaller dispersion because there is no modal dispersion due to multiple propagation modes
- III-V compounds such as InGaAsP (Indium Gallium Arsenide Phosphide) operated at a wavelength of 1300nm. At this wavelength, fibre attenuation is approximately 0.4-0.6 dB/km and fibre dispersion is essentially zero if higher order contributions are ignored
- Transmission distance and speed are essentially limited by attenuation

Third Generation

- In the third generation, further improvement in semiconductor lasers made it possible to generate single longitudinal mode light signals at wavelengths of 1300 and 1500 nm
- The coherence of the output light is much improved because of the single-mode output
- At 1550 nm, the minimum attenuation of 0.2 dB/km can also be achieved
- However, the dispersion is larger than at 1300 nm
- To minimise dispersion and attenuation, dispersion-shifted fibres have been used for transmission at 1550 nm

XL Photonics, 2.5 Gbps DFB Laser Diode Module *XDL0250B-001*



- 1550 nm distributed feedback laser
- Low threshold current
- High optical power available
- 2.5 Gbps (NRZ) direct modulation
- Stable single longitudinal mode operation
- Internal thermoelectric cooler and monitor photodiode
- Built-in optical isolator
- Single mode fiber pigtail with connector ; 25 Ω impedance-matched RF input

Fourth Generation

- In the first three generations, signals were detected incoherently
- In the fourth generation, coherent detection was used to enhance the receiver's sensitivity
- With coherent detection, received signals are amplified by the local carrier, which makes the system performance limited by shot noise
- When coherent detection is used systems can achieve a detection performance of 50 photons per bit
- Using a single frequency source, the distance limit is 210 km, and the capacity-distance product is 2100 Gb/s-km

Fifth Generation

- To eliminate the attenuation and dispersion limits, optical amplifiers and optical fibre solitons have been developed
- Optical amplifiers amplify optical signals directly in the optical domain and are capable of simultaneously amplifying multiple signal wavelengths and this has facilitated Dense Wavelength Division Multiplexing (DWDM)
- Optical amplifiers are used at the end of each fibre span to boost the power of the DWDM signal channels to compensate for fibre attenuation in the span

Fifth Generation

- Erbium-doped fibre amplifiers (EDFA) designed to operate with high inversion provide gain over a spectral range about 30 nm in width, from about 1530 nm to about 1560 nm
- This spectral range can support roughly 40 DWDM signal channels with a separation of 100 GHz and 80 channels with a separation of 50 GHz, corresponding to 400 or 800 Gb/s, respectively, 10Gb/s OC-192 or STM-64 channels
- In the future, with 40-Gb/s channels, capacities of 1.6 Tb/s (1600Gb/s) for 100-GHz spaced channels will be possible

Telecom Windows

- The first window at 800–900 nm was originally used. GaAs/AlGaAs-based laser diodes and light-emitting diodes (LEDs) served as transmitters, and silicon photodiodes were suitable for the receivers.
- However, the fiber losses are relatively high in this region, and fiber amplifiers are not well developed for this spectral region. Therefore, the first telecom window is suitable only for short-distance transmission.

Telecom Windows

- The second telecom window utilizes wavelengths around 1.3 μm, where the loss of silica fibers is much lower and the fibers' chromatic dispersion is very weak, so that dispersive broadening is minimized. This window was originally used for long-haul transmission.
- However, fiber amplifiers for 1.3 μm (based on, e.g. on praseodymium-doped glass) are not as good as their 1.5-μm counterparts based on erbium, and zero dispersion is not necessarily ideal for long-haul transmission, as it can increase the effect of optical nonlinearities.

Telecom Windows

- The third telecom window, which is now very widely used, utilizes wavelengths around 1.5 μm.
- The losses of silica fibers are lowest in this region, and erbium-doped fiber amplifiers are available which offer very high performance.
- Fiber dispersion is usually anomalous but can be tailored with great flexibility (→ dispersion-shifted fibers).

Wavelength bands

The second and third telecom windows are further subdivided into the following wavelength bands:

Band	Description	Wavelength range
O band	original	1260–1360 nm
E band	extended	1360–1460 nm
S band	short wavelengths	1460–1530 nm
C band	conventional (“erbium window”)	1530–1565 nm
L band	long wavelengths	1565–1625 nm
U band	ultralong wavelengths	1625–1675 nm

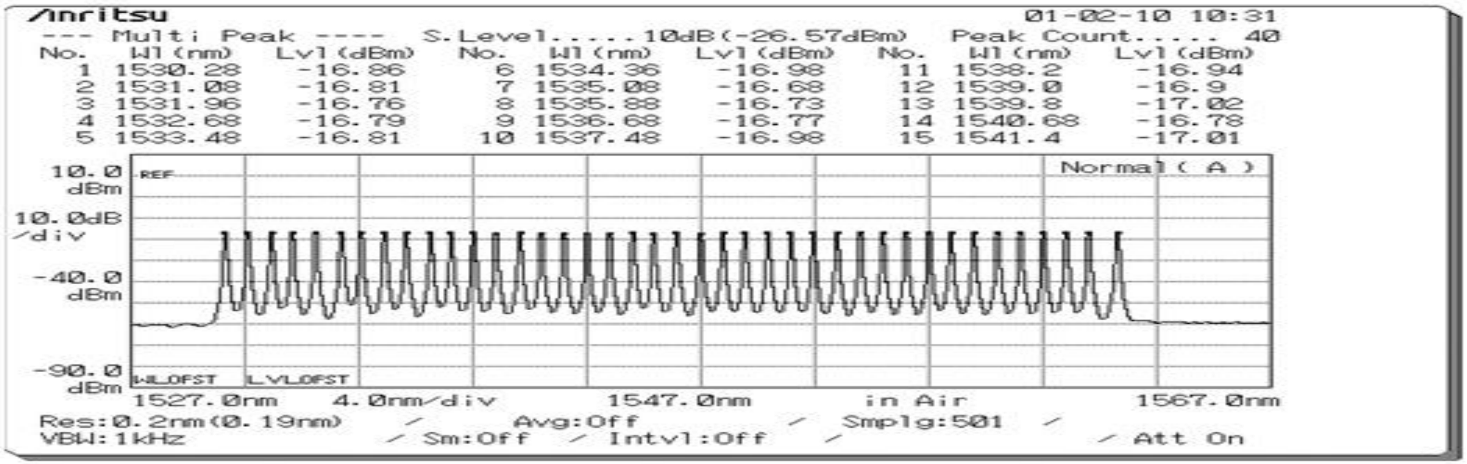
Wavelength bands

The second and third telecom windows were originally separated by a pronounced loss peak around 1.4 μm, but they can effectively be joined with advanced fibers with low OH content which do not exhibit this peak.

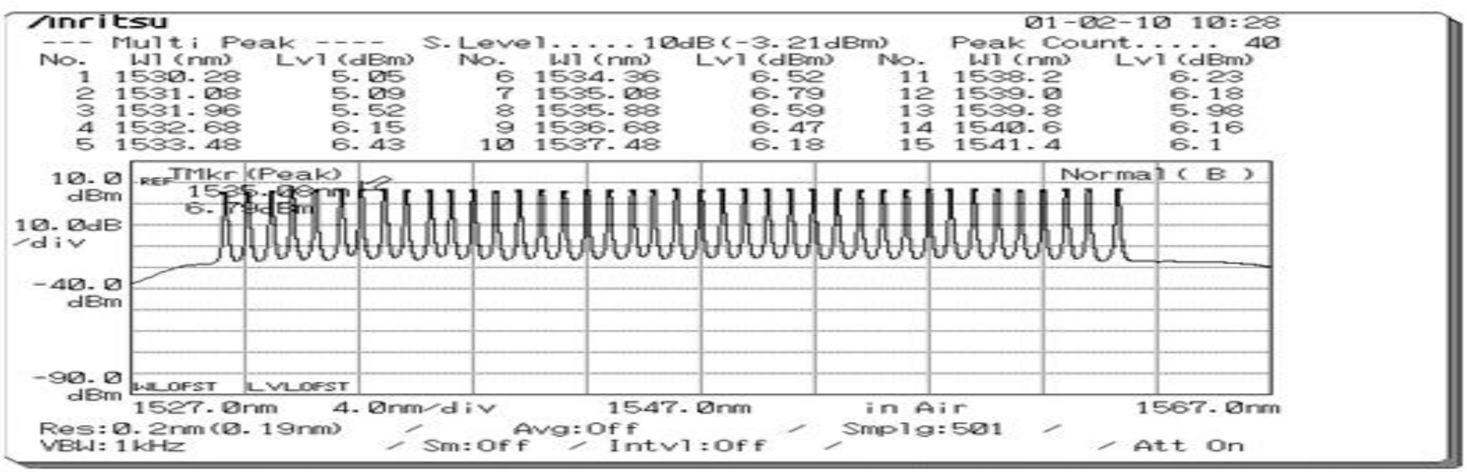
WDM Optical Fiber Amplifier – C band

LiComm WOFA designed for use in high-performance and wide bandwidth DWDM systems of core network and Metropolitan network. It offers high saturated output power, wide flat range, high gain, low noise figure, and automatic gain control (AGC).

Spectrum of input signals



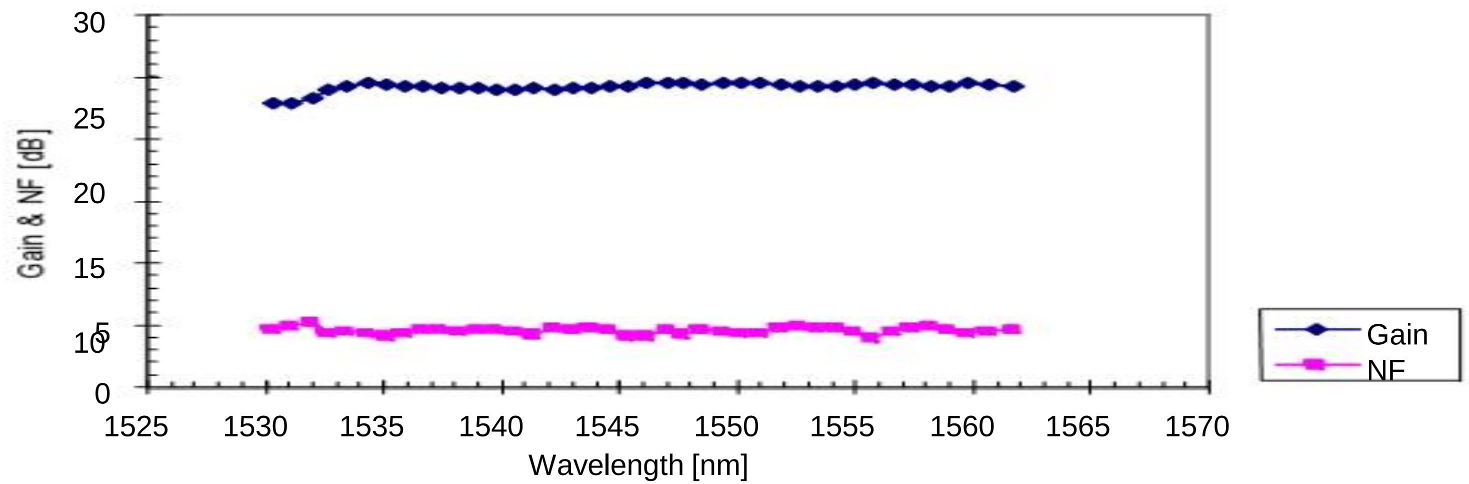
Spectrum of amplified signals

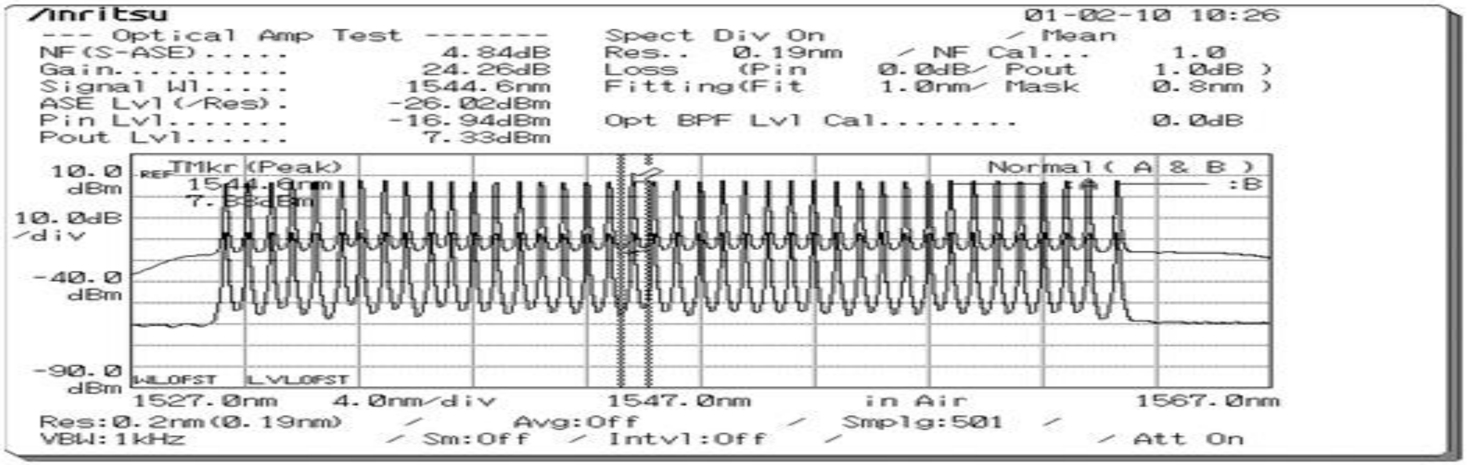


http://www.LiComm.com

Characteristic of gain & noise figure

+23dBm Pout (Pin=-1dBm)





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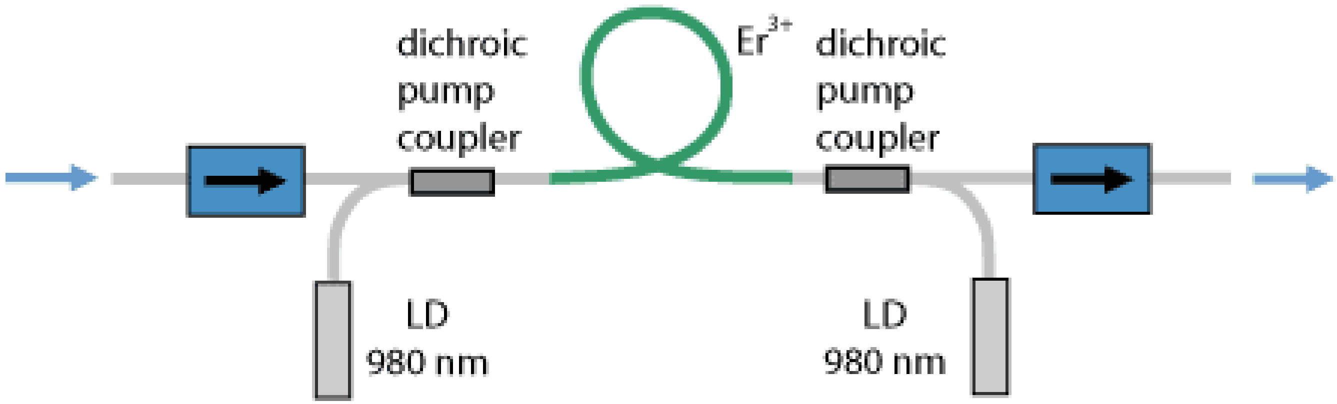
LIGHT COMMUNICATION

Erbium Doped Fibre Amplifier



Schematic setup of a simple erbium-doped fiber amplifier. Two laser diodes (LDs) provide the pump power for the erbium-doped fiber. The pump light is injected via dichroicfiber couplers. Pig-tailed optical isolators reduce the sensitivity of the device to back-reflections.

Erbium Doped Fibre Amplifier

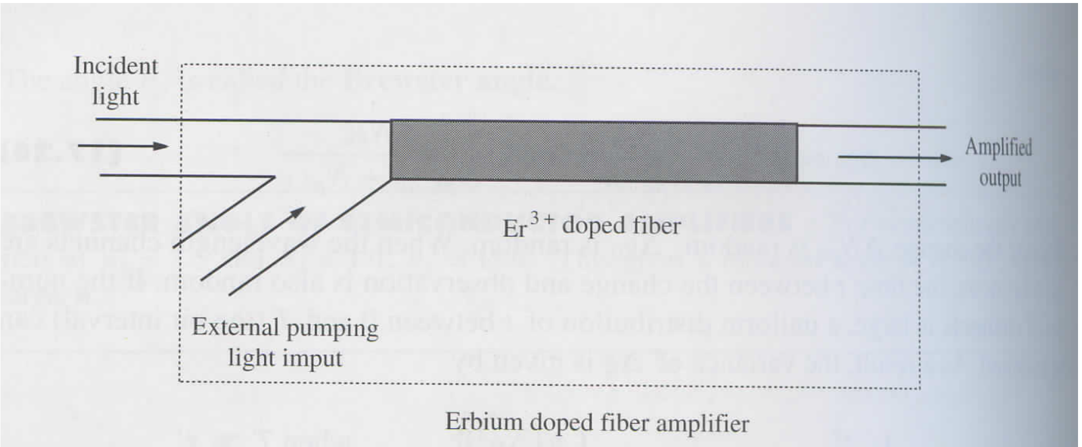


Figure 17.8 Erbium-doped fiber amplifier (EDFA).

Brand-new 980nm pump LD

Pumping at 980nm and 1450 nm is effective

- In order to pump carriers from the ground level to the metastable level a pumping source at wavelength 1450nm, 980nm, or 800nm can be used
- These will excite the carriers to $^4I_{13/2}$, $^4I_{11/2}$ or $^4I_{9/2}$, respectively. Due to their short lifetime excited carriers at $^4I_{11/2}$ or $^4I_{9/2}$ will quickly move down to the metastable level $^4I_{13/2}$.
- The difficulty of finding good laser sources limits pumping to 800, 980, and 1470 nm.

Erbium Doped Fibre Amplifier – Energy Levels
Emission wavelength 1530 nm

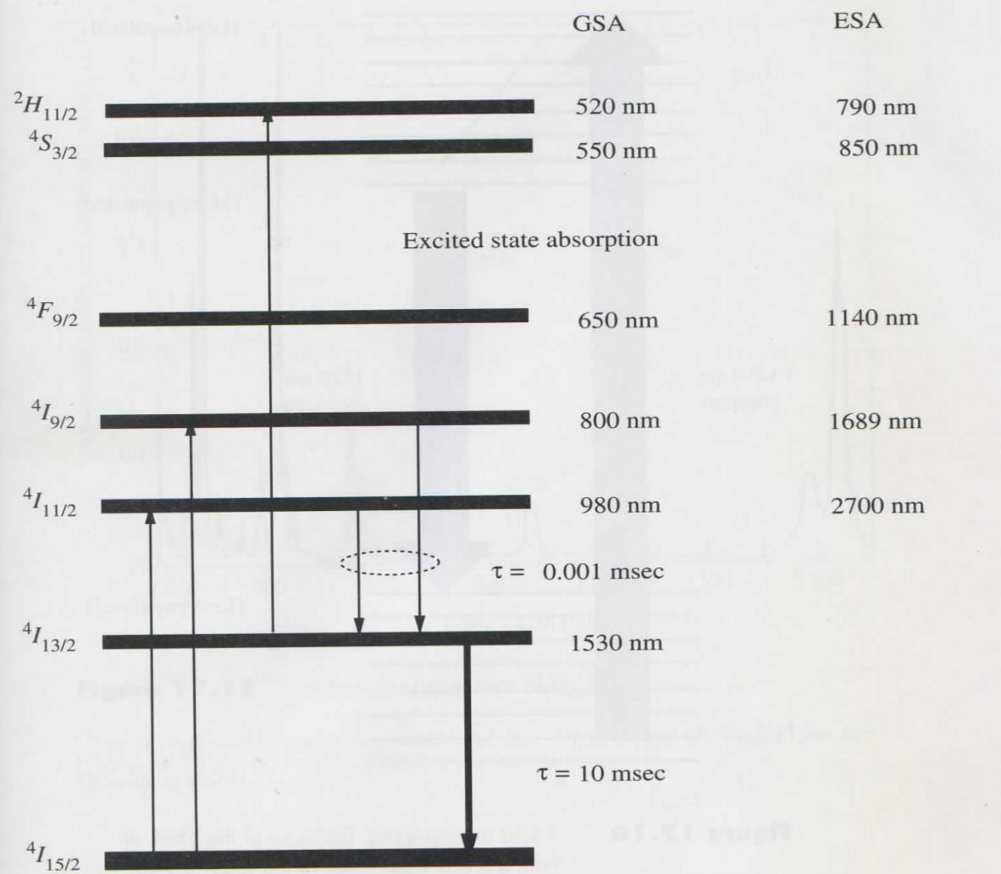


Figure 17.9 Energy levels of Er^{3+}. For each level, the ground state absorption (GSA) wavelength is the light wavelength needed to excite carriers from the ground state to the given level, and the excited state absorption (ESA) wavelength is the light wavelength needed to excite carriers from the given level to the metastable state $^4I_{13/2}$.

Pumping at 800nm is not effective

- Because of the excited absorption (ESA) from $^{4}I_{13/2}$ to $^{2}H_{11/2}$ pumping at 800 nm is not effective
- Therefore, only 980nm and 1470nm pumpings are used practically
- 1470nm sources are generally available
- 980nm has a higher pumping efficiency (around 10dB/mW) compared to 6dB/mW at 1470nm
- 980nm has lower pumping noise, so it is preferred.

Erbium Doped Fibre Amplifier – Energy Levels

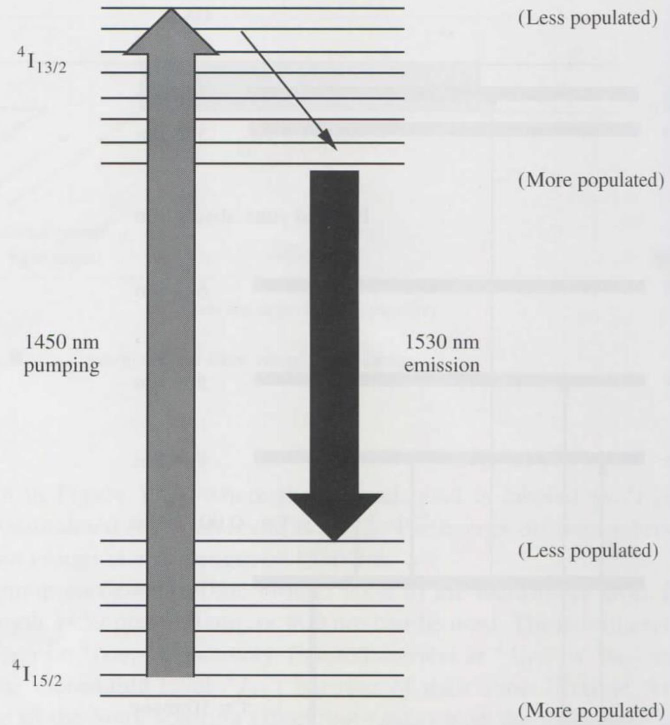


Figure 17.10 1450 nm pumping. Because of the Stark effect, there are splittings at the ground state and the metastable state. At thermal equilibrium, both states have a higher population at their lower bands. Because both the pumping rate and the stimulated emission rate are proportional to the population difference of the two levels, pumping takes place between the lower band of the ground state and the upper band of the metastable state (1450 nm), and stimulated emission takes place between the lower band of the metastable state and the upper band of the ground state (1530 nm).

Absorption and Emission Cross Sections

To quantify the absorption efficiency in external pumping, a parameter called the absorption cross section σ_a is used

By definition, if the pumping power is P_p and the ground state population is N_1 , the pumping rate $W_p N_1$ where:

$$W_p \stackrel{\text{def}}{=} \frac{\sigma_a P_p}{h f_p A} sec^{-1} \quad \dots\dots \qquad (1)$$

Absorption and Emission Cross Sections

hf_p is the photon energy of external pumping at a frequency f_p (Hz) and A is the core area of the EFDA fibre.

From equation (1) a large absorption cross section produces a high pumping efficiency.

Absorption cross sections at 800 nm, 980 nm, and 1450 nm are shown in figures 17.13, 17.14 & 17.15

Absorption Spectrum of Erbium

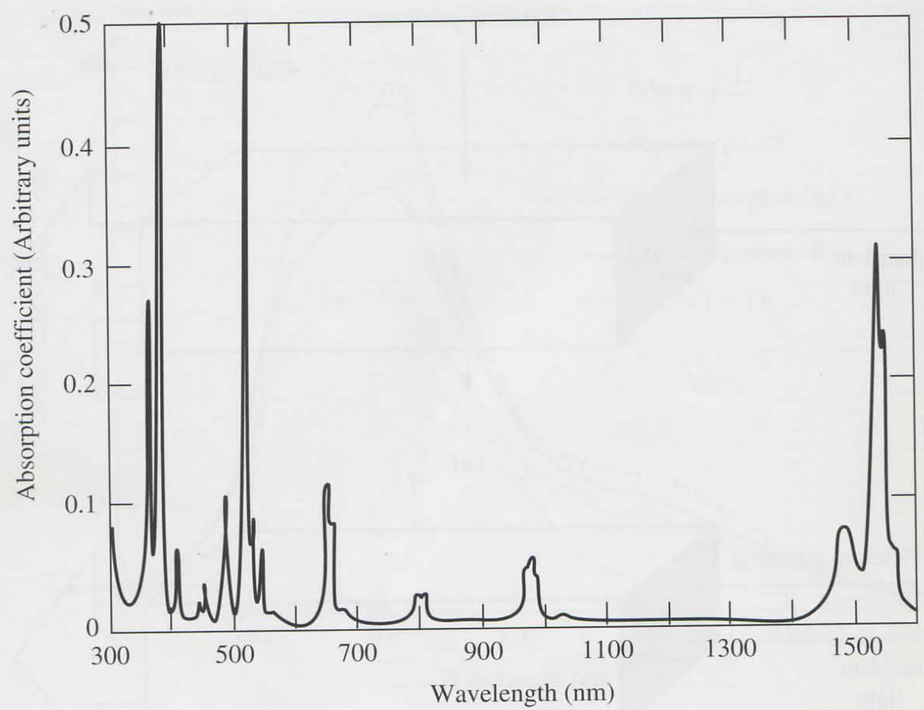


Figure 17.11 Absorption spectrum of Er^{3+}.

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Erbium Doped Fibre Amplifier – Pumping

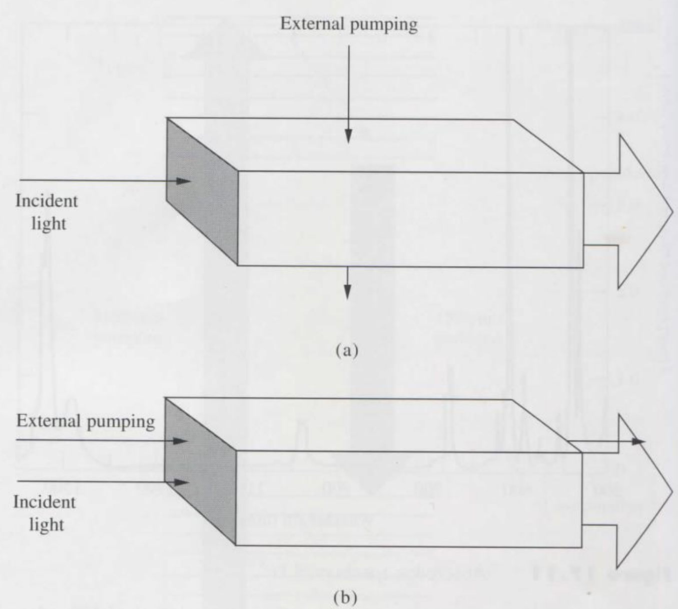

Figure 17.12 Two types of pumping: (*a*) transverse and (*b*) longitudinal.

Table 17.2 Typical EDFA parameters, which can strongly depend on the materials doped.

Parameter	Typical Value
τ_{sp}	10 msec
σ_a	2.5×10^{-21} cm^2 @ 980 nm 1.8×10^{-21} cm^2 @ 1480 nm
σ_e	5×10^{-21} cm^2 @ 1540 nm
$N_t = N_1 + N_2$	8×10^{18} cm^{-3}
Emission bandwidth	30 nm (FWHM)

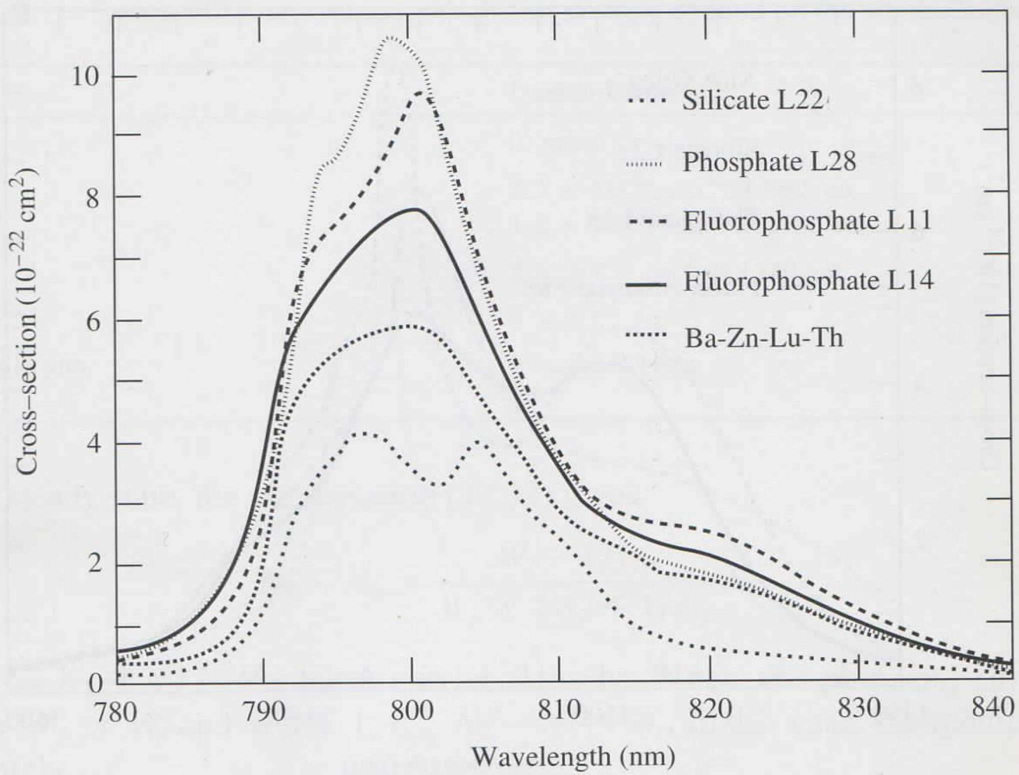

Figure 17.13 Absorption cross section of Er^{3+} at 800 nm.

Source: Reprinted, by permission, from Miniscalco, "Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm," Figure 11 [10]. © 1991 by IEEE.

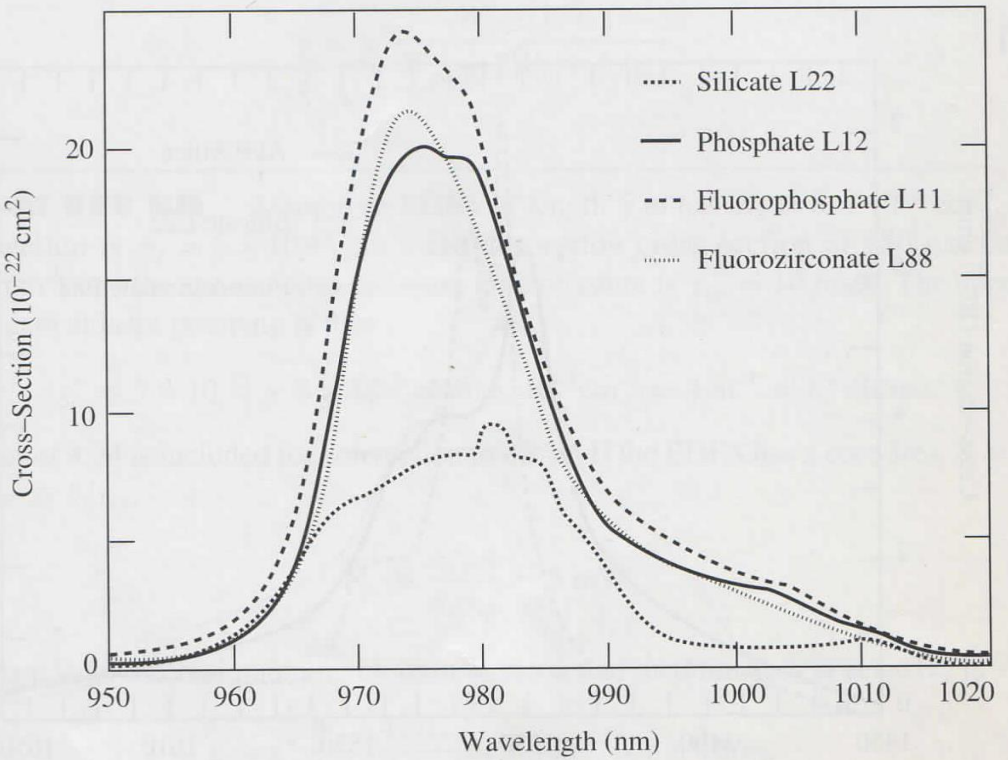

Figure 17.14 Absorption cross section of Er^{3+} at 980 nm.

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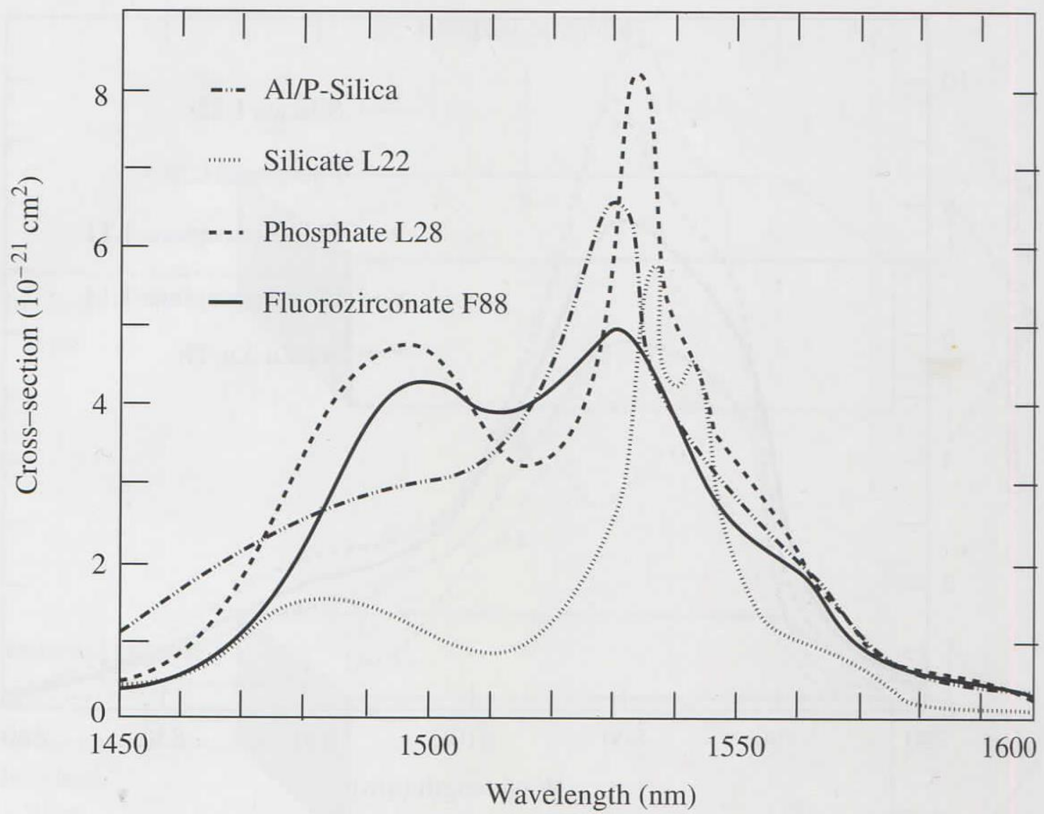

Figure 17.15 Absorption cross section of Er^{3+} at 1450 nm.

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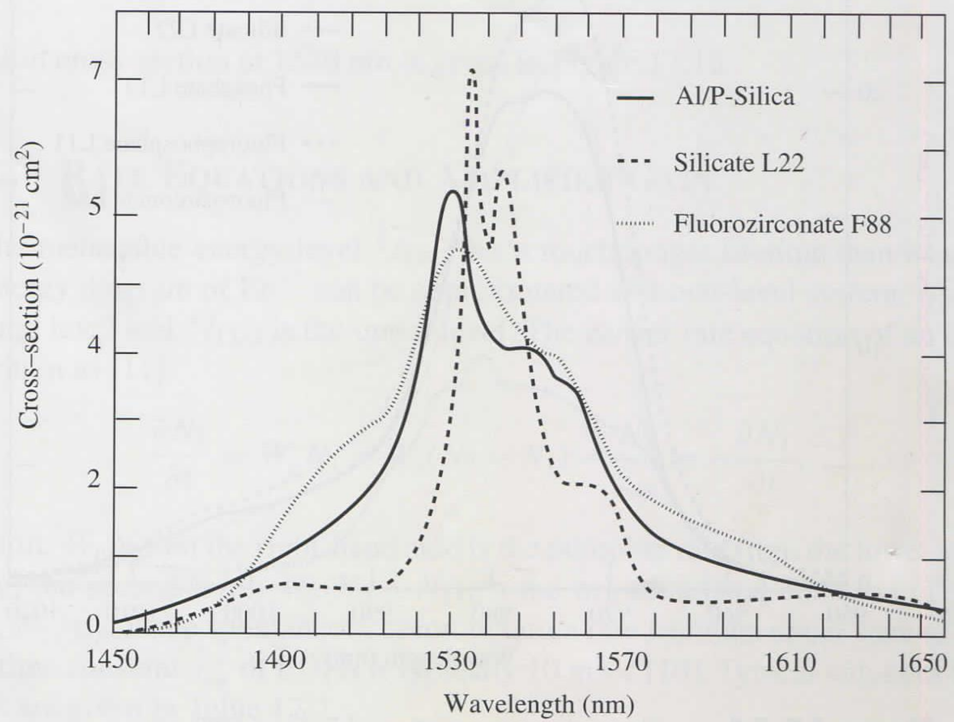

Figure 17.16 Emission cross section of Er^{3+} at 1540 nm.

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Absorption and Emission Cross Sections

P_p is spatially dependent, the amount of power decrease over a short distance dz is:

$dP_p(z) = -\sigma_a P_p(z) N_1 dz$ ……………………*(2)*

When $\sigma_a N_1$ is constant along the fibre,
$P_p(z)$ has an exponential decay

In addition to the absorption cross section that determines the pumping rate, there is an emission cross section that determines the medium gain. The medium gain is:

$g = \sigma_e(N_2 - N_1)$ ………………………(3)

Where N_2 and N_1 are the carrier densities at the metastable and ground states

Stimulated Emission

From (3) the stimulated emission rate is

$$R_s = v_g g N_{ph} = \frac{\sigma_e P_{in}}{h f_s A}(N_2 - N_1) \stackrel{\text{def}}{=} W_s (N_2 - N_1) \quad \ldots .(4)$$

Where $P_{in} = v_g N_{ph} \mathrm{A}$ is the incident light power, hf_s is the photon energy of the input signal, v_g is propagation velocity, N_{ph} is the photon density and

$$W_s \stackrel{\text{def}}{=} \frac{\sigma_e P_{in}}{h f_s A} \; sec^{-1} \qquad (5)$$

Carrier Rate Equation

Because the metastable energy level $^4.I_{13/2}$ has a much longer lifetime than its upper levels, the energy diagram of Er^{+3} can be approximated as a two level system, where $^4.I_{15/2}$ is the ground level and $^4.I_{13/2}$ is the upper level. The carrier rate equation of an EDFA can be written as:

$$\frac{\partial N_2}{\partial t} = W_p N_1 - W_s (N_2 - N_1) - \frac{N_2}{\tau_{sp}} = - \frac{\partial N_1}{\partial t} \qquad (6)$$

$W_p N_1$ is the pumping rate from the lower state to the upper state

$W_s(N_2 - N_1)$ is the net stimulated emission rate

$\frac{N_2}{\tau_{sp}}$ is the spontaneous recombination rate from the upper to the lower state

Upper Limit of Gain

In the steady state, the rate equation (6) gives

$$N_2 - N_1 = \frac{W_p - 1/\tau_{sp}}{W_p + 2W_s + 1/\tau_{sp}} N_t \qquad (7)$$

where $N_t \overset{\text{def}}{=} N_1 + N_2$ is the total carrier density. When the pumping rate is high enough , or $W_p \gg W_s$ and $W_p \gg 1/\tau_{sp}$, $N_2 - N_1 \approx N_t$

In this case the medium gain is approx:

$$g = \sigma_e (N_2 - N_1) \approx \sigma_e N_t \overset{\text{def}}{=} g^* \qquad (8)$$

Where g^* is the upper limit of the medium gain constant

$$g = g^* \frac{W_p - 1/\tau_{sp}}{W_p + 2W_s + 1/\tau_{sp}} \qquad (9)$$

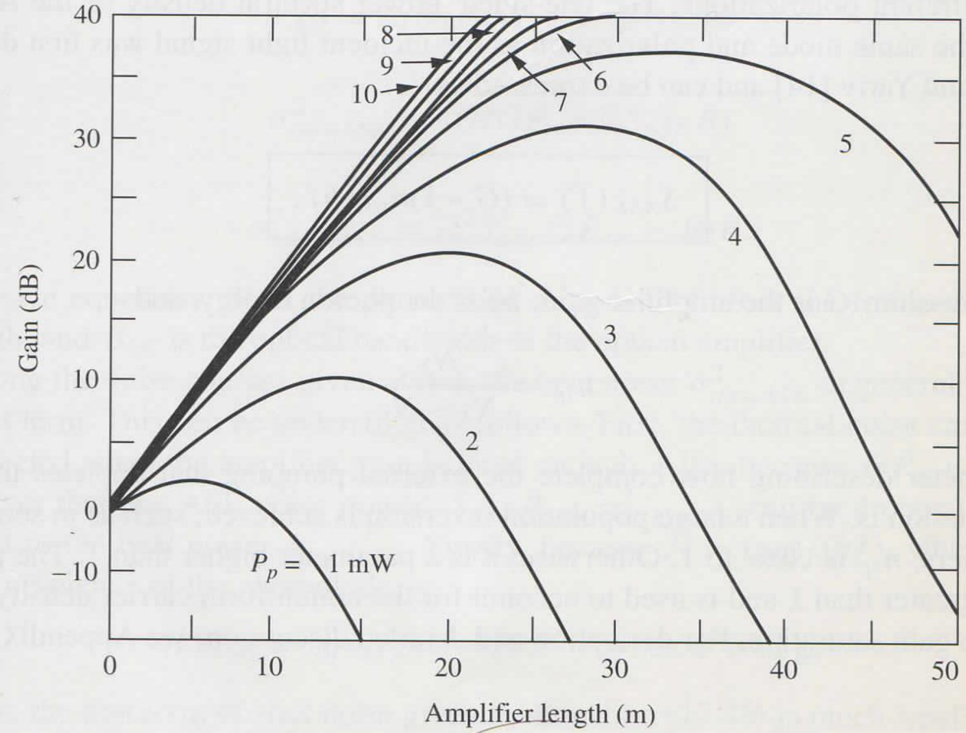


Figure 17.17 EDFA gain as a function of the amplifier length.

Source: Reprinted, by permission, from Giles and Desurvire, "Modeling Erbium-Doped Fiber Amplifiers," Figure 8b [12]. © 1991 by IEEE.

- The pumping rate W_p is spatially dependent because:
- $\frac{dP_p}{dz} = -(\sigma_a N_1)P_p$ (10)
- and
- $\frac{dP_{in}}{dz} = gP_{in} \simeq \sigma_e(N_2 - N_1)P_{in}$ (11)
- From (7) & (8) we obtain
- $\frac{dP_p}{dz} = -(\sigma_a N_t)P_p \left\{\frac{W_s+\frac{1}{\tau_{sp}}}{W_p+2W_s+\frac{1}{\tau_{sp}}}\right\}$ $Eq\ (12)$

Error equation (13) Should be $\frac{dP_{in}}{dz} =$

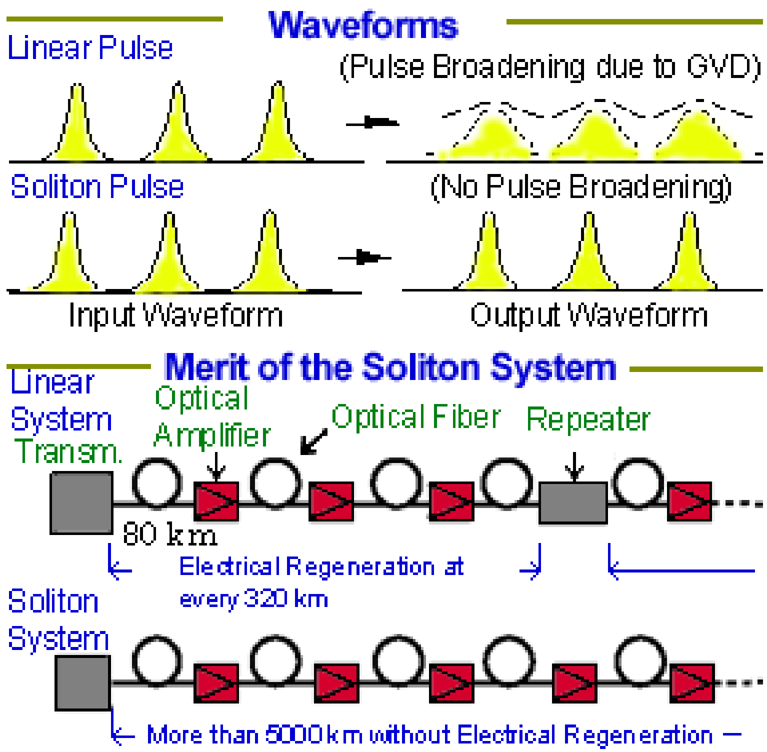
- And
- $\frac{dP_p}{dz} = g^* \left\{ \frac{W_s - \frac{1}{\tau_{sp}}}{W_p + 2W_s + \frac{1}{\tau_{sp}}} \right\} P_{in} = \left\{ \frac{g_0}{1 + {W_s}/{W_{sat}}} \right\} P_{in}$ (13)
- Where
- $g_0 = g^* \left\{ \frac{W_p - \frac{1}{\tau_{sp}}}{W_p + \frac{1}{\tau_{sp}}} \right\}$ (14)
- Is the medium gain at zero incident signal and
- $W_{sat} = \frac{1}{2} (W_p - \frac{1}{\tau_{sp}})$ (15)
- Is the saturation rate. Because W_{sat} becomes smaller as Wp gets smaller along the light propagation direction gain saturationeffect is stronger at the output end of the amplifier.

Optimum EDFA length

- If W_s is large compared with W_p and W_s is large compared with $1/\tau_{sp}$, simplify equation (12) and integrate the simplified equation to produce an analytical expression for the optimum amplifier length L at which point $W_p(L) = 1/\tau_{sp}$.
- $\frac{dP_p}{dz} \cong -\frac{(\sigma_a N_t)P_p}{2}$ (16)
- Therefore integrating we get between the limits 0 to Z
- gives $P_p(z) = P_p(0)e^{-\sigma_a N_t z/2}$ (17)
- The optimum amplifier length L occurs at the point $W_p(L) = 1/\tau_{sp}$

- The optimum amplifier length L occurs at the point $W_p(L) = 1/\tau_{sp}$
- Hence
- $W_p = \frac{\sigma_a P_p}{h f_p A} = 1/\tau_{sp}$ (18)
- $P_p(z) = \frac{h f_p A}{\sigma_a} . 1/\tau_{sp}$ (19)
- At $z = L = \frac{2}{N_t \sigma_a} ln\left[P_p(0)\sigma_a \tau_{sp}/h f_p A\right]$

Network Innovation Laboratories-NTT



NTT succeeded in the Dispersion Managed soliton transmission of 40 Gbit/s - 1020 km and 20 Gbit/s - 2040 km using the optical fiber cable installed between Mito and Maebashi (170 km)

Summary

- A communication network consists of interconnected links, each of which has three basic elements: transmitter, channel, receiver
- A communication system is a point-to-point transmission link that can be implemented by:
  – Baseband or passband transmission
  – Digital or analogue modulation
  – Coherent or incoherent detection
- All optical communication systems are passband at visible or infrared frequencies. They can be digital or analogue, coherent or incoherent

Summary

- Line coding and modulation are used to convert input signals into forms suitable for transmission. Line coding is used for digital transmission and modulation is used for passband communications
- Advantages of optical fibre communication include:
  - Large transmission capacity
  - Low attenuation
  - Interference immunity
  - High speed interconnection capability
  - Parallel transmission
- The focus of lightwave technology development is to increase transmission distance and capacity. Low loss fibres and single-mode light sources are the keys to accomplishing these objectives

End